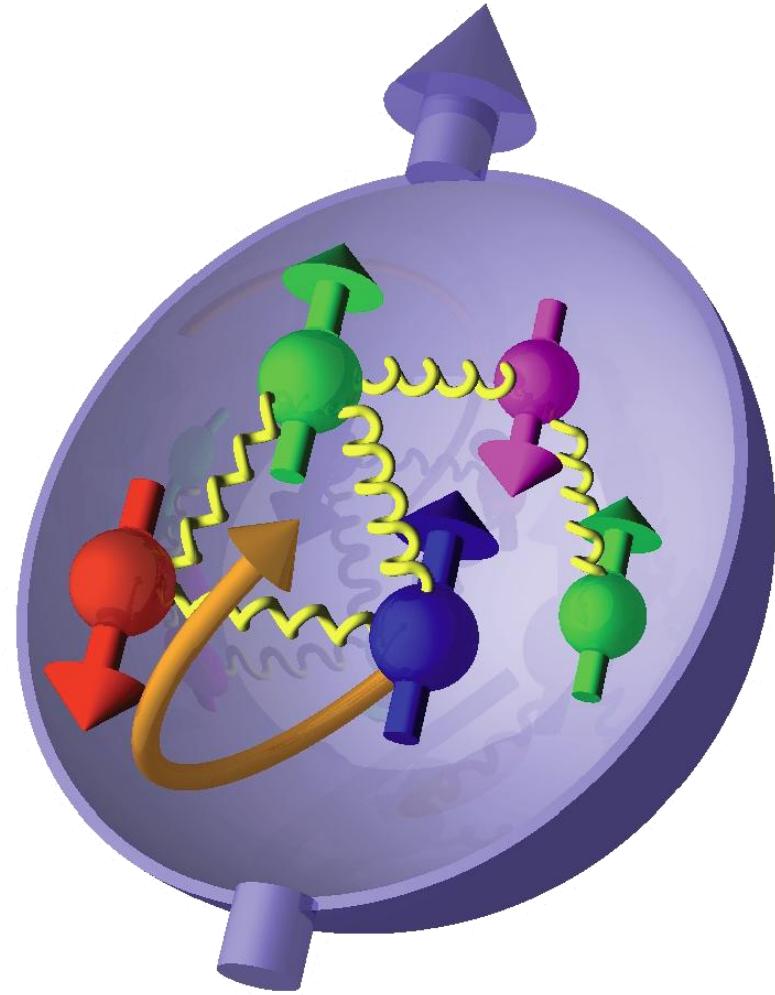


New Experimental Information on Quark's Angular Momentum

Jin Huang
MIT
P-25 Seminar
Aug 30, 2010 @ LANL

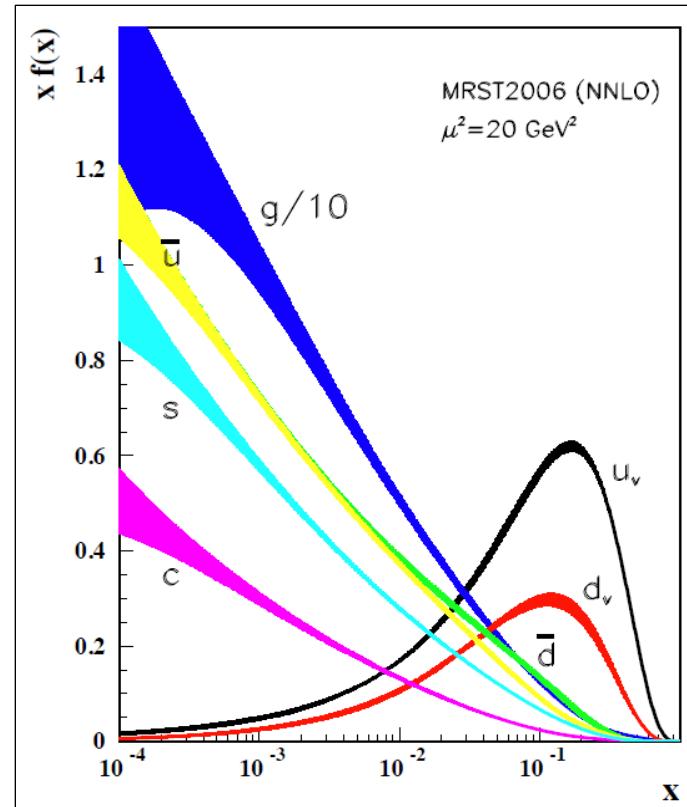
nucleon structure

- ▶ >99% mass of visible matter around us is in nucleons
- ▶ <2% of nucleon mass is quark mass (Higgs mechanism ?)
- ▶ Rest due to interaction of quarks and gluon fields
 - Not fully understood from first principal
 - Important to study



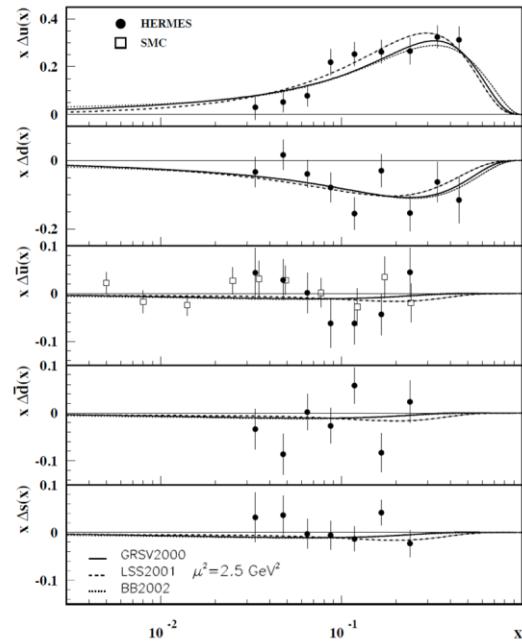
Parton Distribution Functions

- ▶ Large portion of knowledge summarized as **Parton Distribution Functions (PDF)**
- ▶ **Un-polarized PDF**
 - Longitudinal momentum distribution
- 1970s: SLAC DIS → Bjorken Scaling, discovery of partons (quarks)
 - Well probed for 40 years over **5 orders in x range and Q^2**
 - Extracted through global analysis

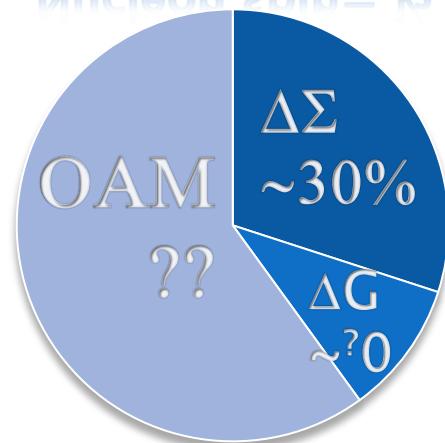


Longitudinal Polarized PDF

- ▶ Longitudinal Polarized PDF
 - Helicity distribution of partons
 - 3 decades study on longitudinally polarized structure:
3 orders in x and 2 in Q^2
- ▶ Spin structure of nucleon
 - Two mainstream definitions
 - $\frac{1}{2} = (\frac{1}{2})\Delta\Sigma + \Delta G + L_q + L_g$ (light-cone gauge)
 - $\frac{1}{2} = (\frac{1}{2})\Delta\Sigma + J_G + Lq$ (gauge invariant)
 - ‘spin crisis’: $\Delta\Sigma \sim 30\%$!
 - Gluon polarization ΔG : small
 - Orbital angular momentum (OAM) important?
 - Largely unknown
 - Could be probed through GPDs
 - New windows to probe?

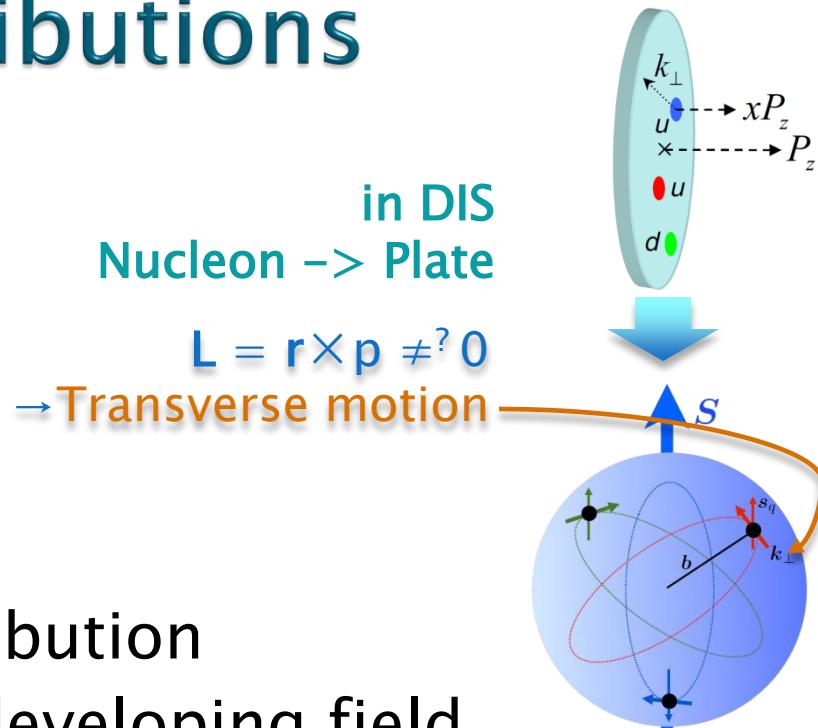


Nucleon spin = $\frac{1}{2}$



Transverse Momentum Dependent (TMD) Partonic Distributions

- ▶ TMDs link
 - Intrinsic motion of partons
 - Parton spin
 - Spin of the nucleon
- ▶ Probes orbital motion of quarks through quark transverse momentum distribution
- ▶ A new phase of study, fast developing field
 - Great advance in theories (models, factorization, Lattice ...)
 - Not measured until recent years
 - Semi-Inclusive DIS (SIDIS): HERMES, COMPASS, JLab, ...
 - p-p(p_bar) process (Drell-Yan, hadron prod, jets) : FNAL, BNL, ...



Leading-Twist TMDs

→ Nucleon Spin
→ Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 = \bullet$		$h_1^\perp = \bullet - \bullet$ Boer-Mulder
	L		$g_1 = \bullet \rightarrow - \bullet \rightarrow$ Helicity	$h_{1L}^\perp = \bullet \rightarrow - \bullet \rightarrow$ Worm Gear
	T	$f_{1T}^\perp = \bullet \uparrow - \bullet \downarrow$ Sivers	$g_{1T} = \bullet \uparrow - \bullet \uparrow$ Worm Gear	$h_{1T} = \bullet \uparrow \uparrow - \bullet \downarrow \uparrow$ Transversity $h_{1T}^\perp = \bullet \uparrow \rightarrow - \bullet \downarrow \rightarrow$ Pretzelosity



: Survive trans. momentum integral

Leading-Twist TMDs

→ Nucleon Spin
→ Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 = \text{○} \cdot \text{○}$		$h_1^\perp = \text{○} \downarrow \text{○} \uparrow$ Boer-Mulder
	L		$g_1 = \text{○} \rightarrow \text{○} \leftarrow$ Helicity	$h_{1L}^\perp = \text{○} \nearrow \text{○} \nwarrow$ Worm Gear
	T	$f_{1T}^\perp = \text{○} \uparrow \text{○} \downarrow$ Sivers	$g_{1T} = \text{○} \uparrow \text{○} \uparrow$ Worm Gear	$h_{1T} = \text{○} \uparrow \text{○} \downarrow$ Transversity $h_{1T}^\perp = \text{○} \nearrow \text{○} \nwarrow$ Pretzelosity



: Contribute to inclusive DIS (quark mass ignored)

Leading-Twist TMDs

→ Nucleon Spin
→ Quark Spin

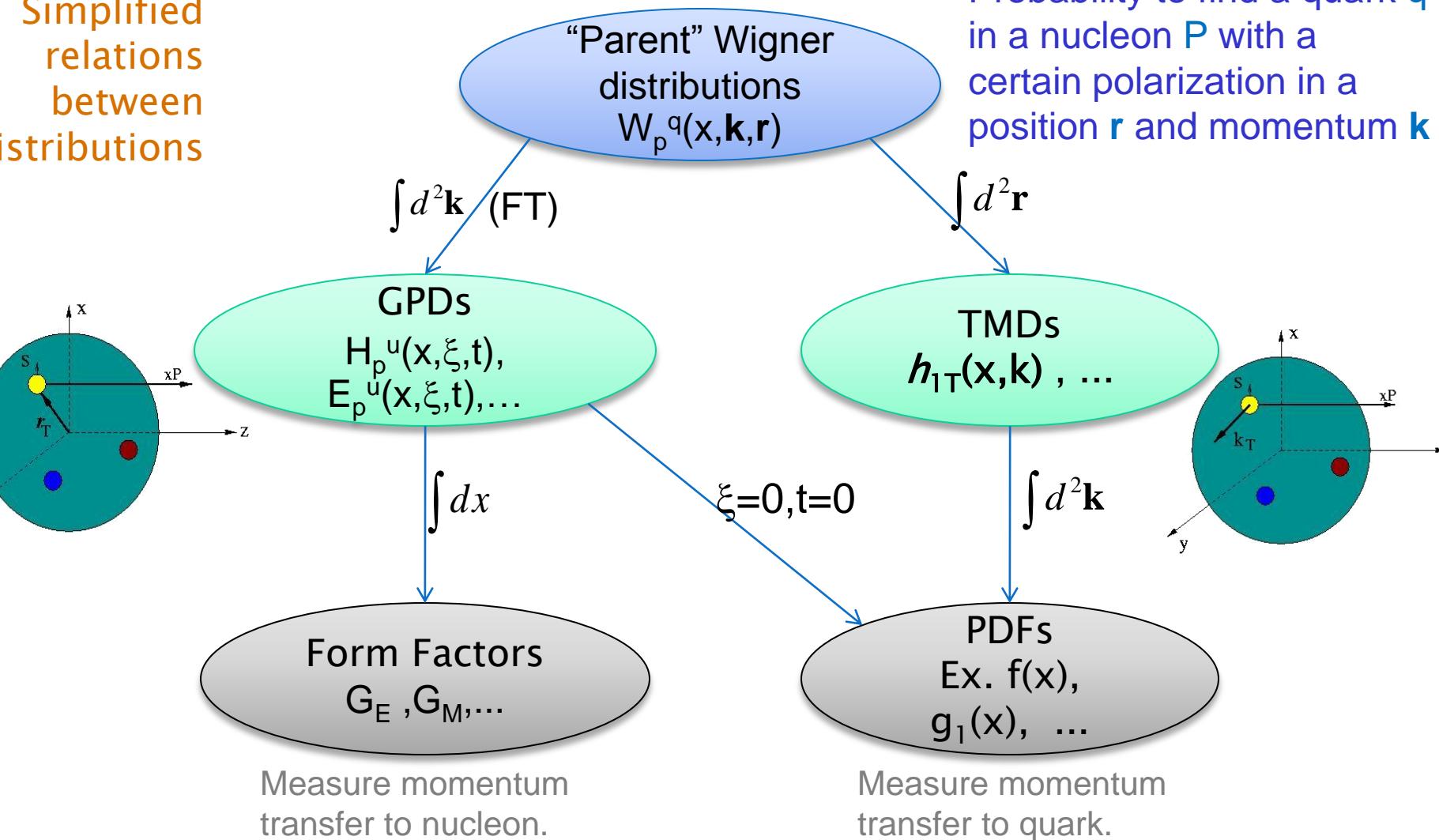
		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 = \bullet$		$h_1^\perp = \bullet - \bullet$ Boer-Mulder
	L		$g_1 = \bullet \rightarrow - \bullet \rightarrow$ Helicity	$h_{1L}^\perp = \bullet \rightarrow - \bullet \rightarrow$ Worm Gear
	T	$f_{1T}^\perp = \bullet \uparrow - \bullet \downarrow$ Sivers	$g_{1T} = \bullet \uparrow - \bullet \uparrow$ Worm Gear	$h_{1T} = \bullet \uparrow \downarrow - \bullet \downarrow \uparrow$ Transversity $h_{1T}^\perp = \bullet \uparrow \rightarrow - \bullet \rightarrow \uparrow$ Pretzelosity



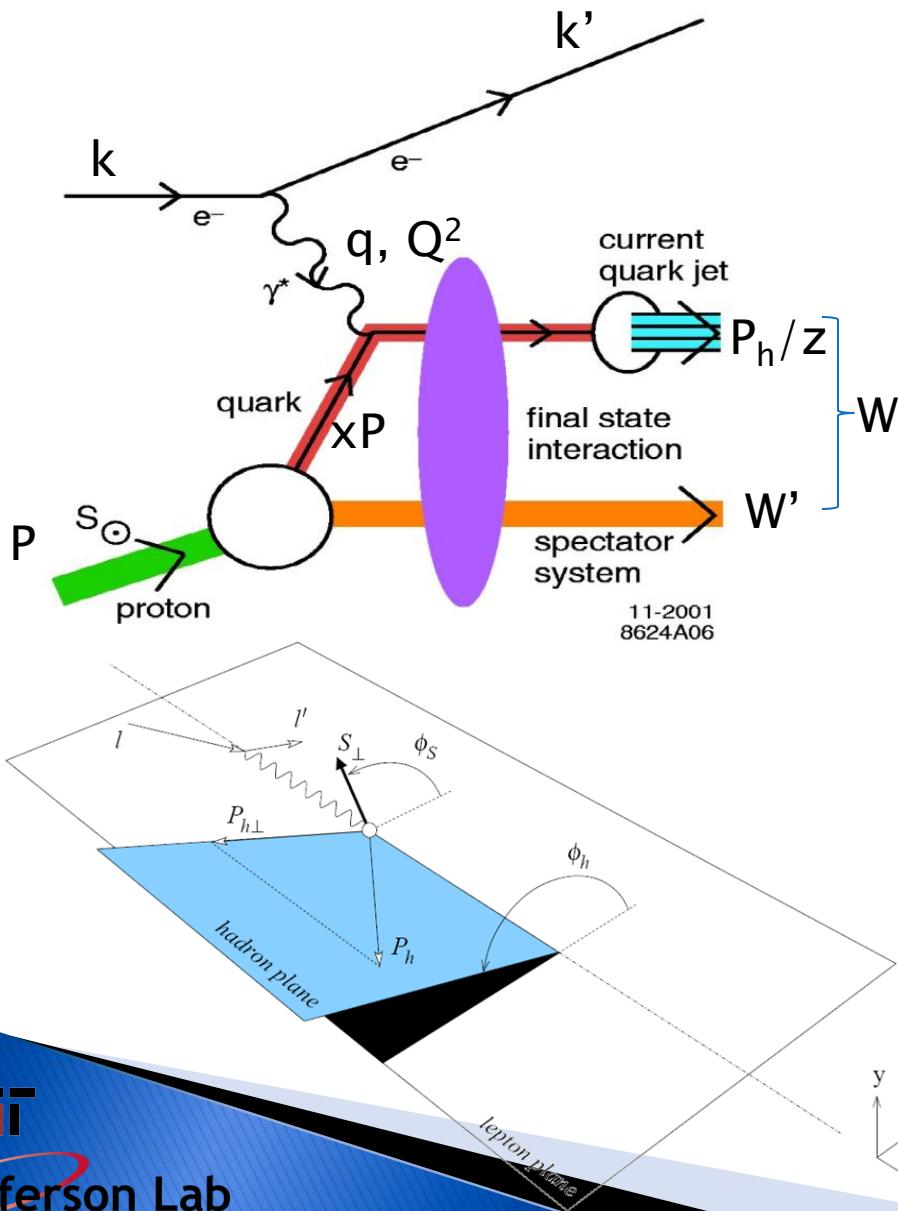
: T-odd. Rest are T-even

TMD : An important view of nucleon

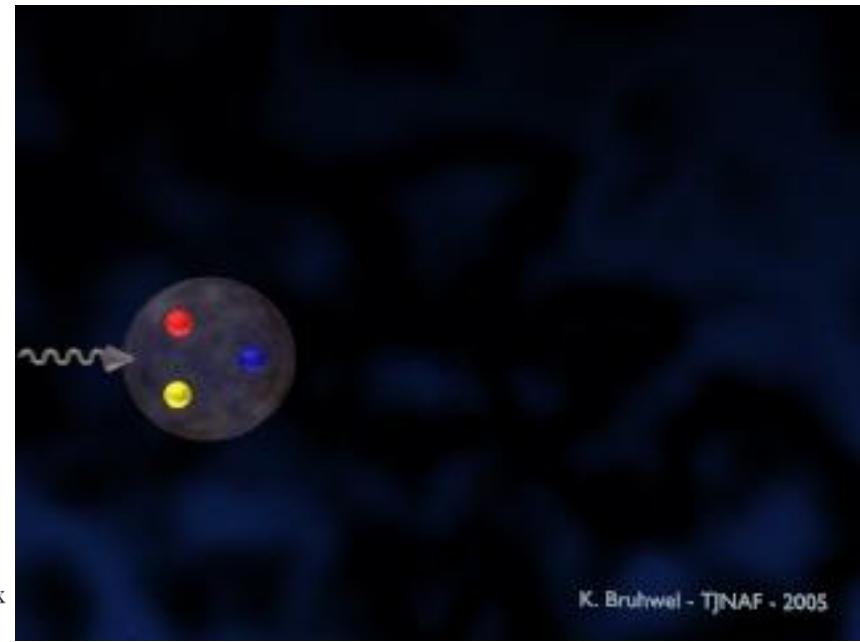
Simplified
relations
between
distributions



One tool to study TMDs: SIDIS



- ▶ Access to new TMDs not accessible in inclusive DIS ($m_{\text{quark}}=0$)
- ▶ Variables:
 x, q, Q^2, z, W, W'



TMDs in SIDIS Cross Section

$$\frac{d\sigma}{dxdydzd\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)}.$$



$$\{F_{UU,T} + \dots$$

Unpolarized

Boer-Mulder $h_{1\perp} = \begin{array}{c} \bullet \\ \downarrow \end{array} - \begin{array}{c} \uparrow \\ \bullet \end{array}$

$$+ \varepsilon \cos(2\phi_h) \cdot F_{UU}^{\cos(2\phi_h)} + \dots$$

Worm Gear $h_{1L\perp} = \begin{array}{c} \bullet \\ \nearrow \end{array} - \begin{array}{c} \nearrow \\ \bullet \end{array}$

$$+ S_L [\varepsilon \sin(2\phi_h) \cdot F_{UL}^{\sin(2\phi_h)} + \dots]$$

Transversity $h_{1T\perp} = \begin{array}{c} \uparrow \\ \bullet \end{array} - \begin{array}{c} \bullet \\ \uparrow \end{array}$

$$+ S_T [\varepsilon \sin(\phi_h + \phi_S) \cdot F_{UT}^{\sin(\phi_h + \phi_S)} + \dots]$$

Sivers $f_{1T\perp} = \begin{array}{c} \bullet \\ \uparrow \end{array} - \begin{array}{c} \bullet \\ \downarrow \end{array}$

$$+ \sin(\phi_h - \phi_S) \cdot (F_{UL}^{\sin(\phi_h - \phi_S)} + \dots)$$

Pretzelosity $h_{1T\perp} = \begin{array}{c} \uparrow \\ \nearrow \end{array} - \begin{array}{c} \nearrow \\ \uparrow \end{array}$

$$+ \varepsilon \sin(3\phi_h - \phi_S) \cdot F_{UT}^{\sin(3\phi_h - \phi_S)} + \dots]$$

Helicity $g_1 = \begin{array}{c} \bullet \\ \nearrow \end{array} - \begin{array}{c} \nearrow \\ \bullet \end{array}$

$$+ S_L \lambda_e [\sqrt{1 - \varepsilon^2} \cdot F_{LL} + \dots]$$

Worm Gear $g_{1T} = \begin{array}{c} \uparrow \\ \bullet \end{array} - \begin{array}{c} \bullet \\ \uparrow \end{array}$

$$+ S_T \lambda_e [\sqrt{1 - \varepsilon^2} \cos(\phi_h - \phi_S) \cdot F_{LT}^{\cos(\phi_h - \phi_S)} + \dots]$$

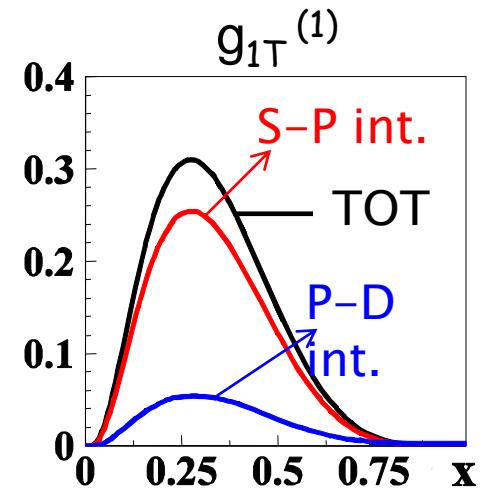
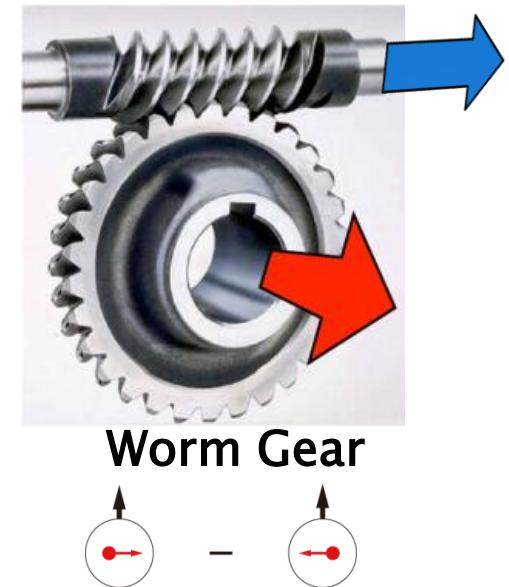
Polarized Target

Polarized Beam and Target

S_L, S_T : Target Polarization; λ_e : Beam Polarization

g_{1T} Distribution Function

- ▶ g_{1T} DF describe quark longitudinal polarization in a transversely polarized nucleon
- ▶ Such polarization can be non-vanishing only if the Orbital Angular Momentum is non-zero
- ▶ Dominated by real part of interference between $L=0$ and $L=1$
 - imaginary part \rightarrow Sivers effect



Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

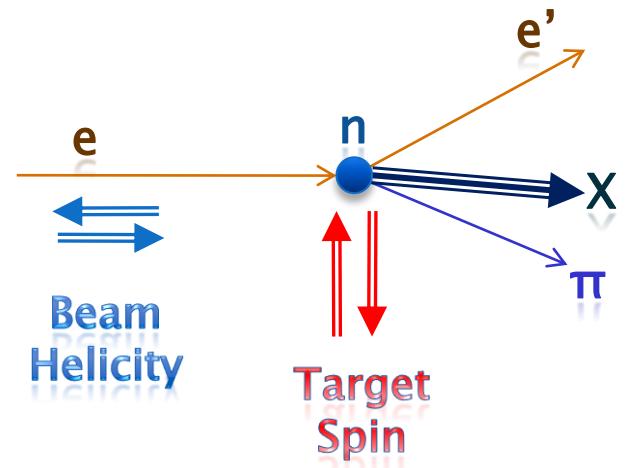
Experimental Extraction of g_{1T}

- ▶ Extractable from Double Beam–Target Spin Asymmetry (DSA) in SIDIS with transversely polarized target: A_{LT}

- ▶
$$\frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} = \dots + S_T \lambda_e [\sqrt{1 - \varepsilon^2} \cos(\phi_h - \phi_S) \cdot F_{LT}^{\cos(\phi_h - \phi_S)} + \dots] \}$$

- ▶ Then

$$A_{LT}^{\cos(\phi_h - \phi_s)} \equiv 2 \frac{\int d\phi_s^h (d\vec{\sigma} - d\bar{\vec{\sigma}}) \cos(\phi_h - \phi_s)}{\int d\phi_s^h (d\vec{\sigma} + d\bar{\vec{\sigma}})} \propto F_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$



Predictions of g_{1T}

► Relations to other TMDs

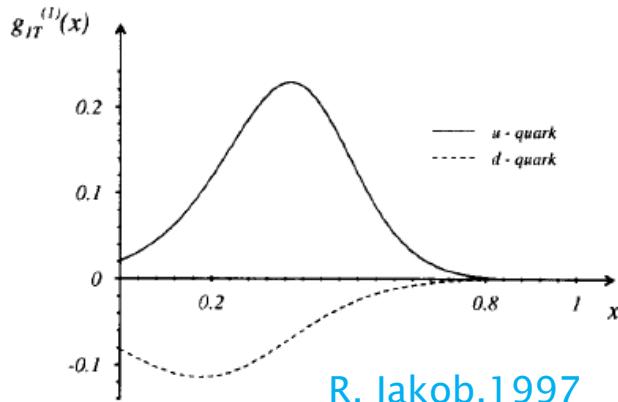
- Cilindrical symmetries

$$g_{1T}(x, k_\perp) = -h_{1L}(x, k_\perp)$$

$$\left(g_{1T}(x, k_\perp)\right)^2 + 2 h_1^\perp(x, k_\perp) h_{1T}^\perp(x, k_\perp) = 0$$

► Numerical predictions

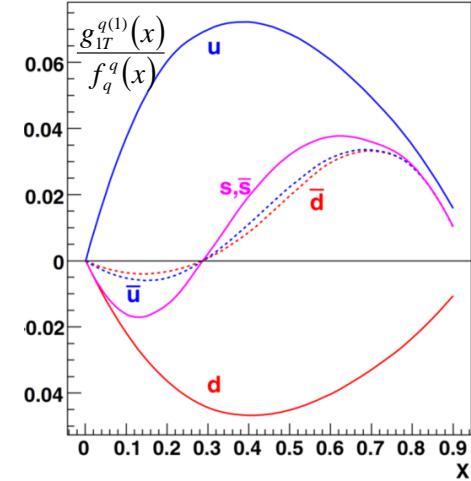
- Spectator Model



- Data of g_1 PDF through Lorentz invariance relations and WW relation,

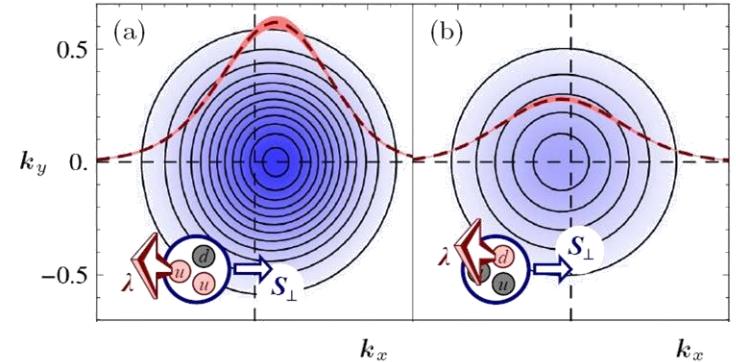
$$g_1(x) + g_2^{\text{WW}}(x) = \int_x^1 dy \frac{g_1(y)}{y}$$

A. Kotzinian, 2006



- Among first TMDs calculated on lattice

Haegler, 2009

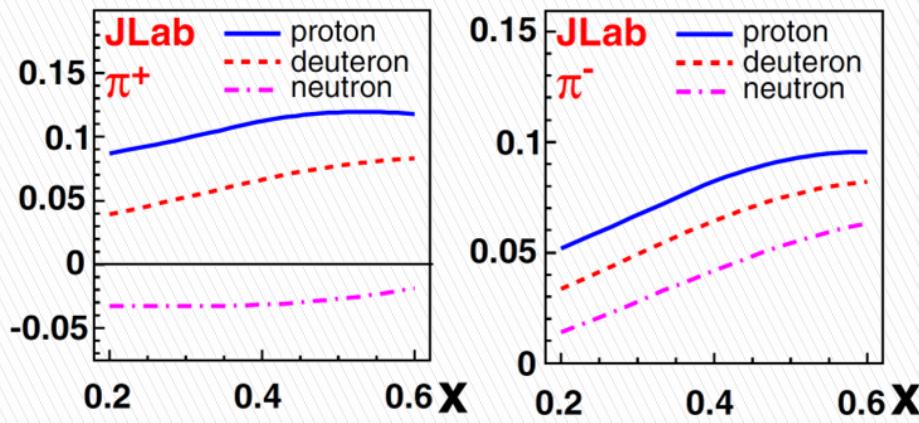


Predictions of A_{LT}

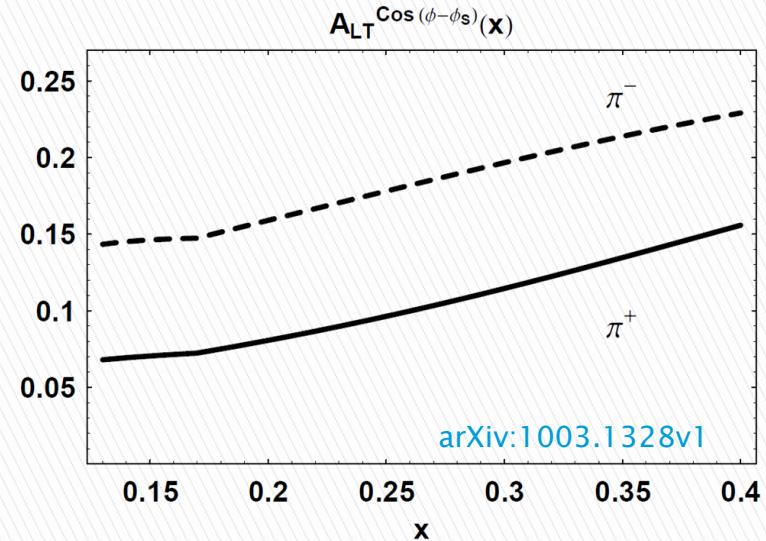
- Models predict few~20 percent asymmetry for
 - Neutron A_{LT}
 - Jlab kinematics

g_1 Data + WW relation

A. Kotzinian, etc., PRD 73 114017 (2006)

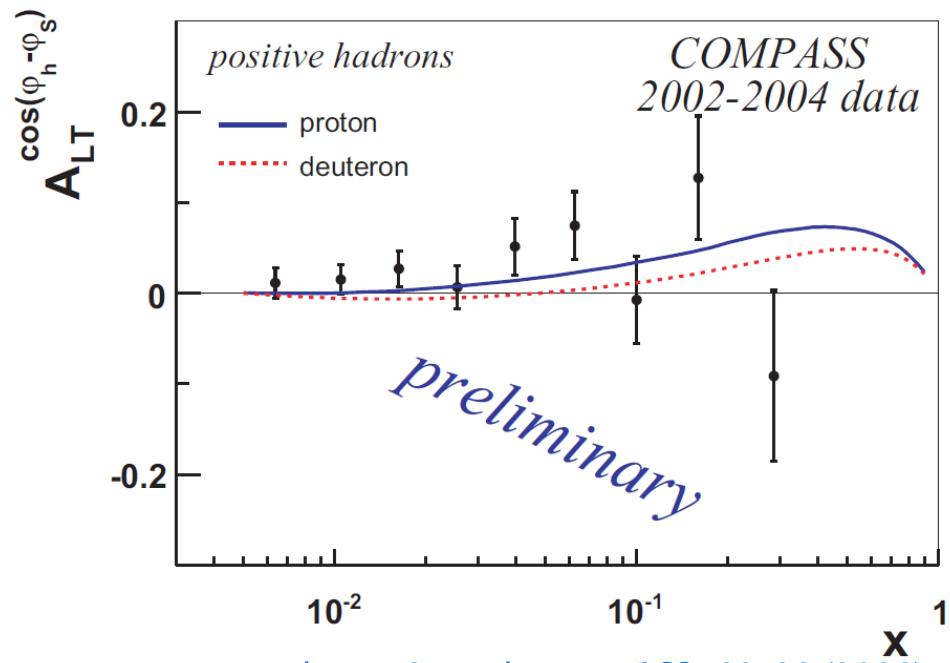


Diquark Spectator Model



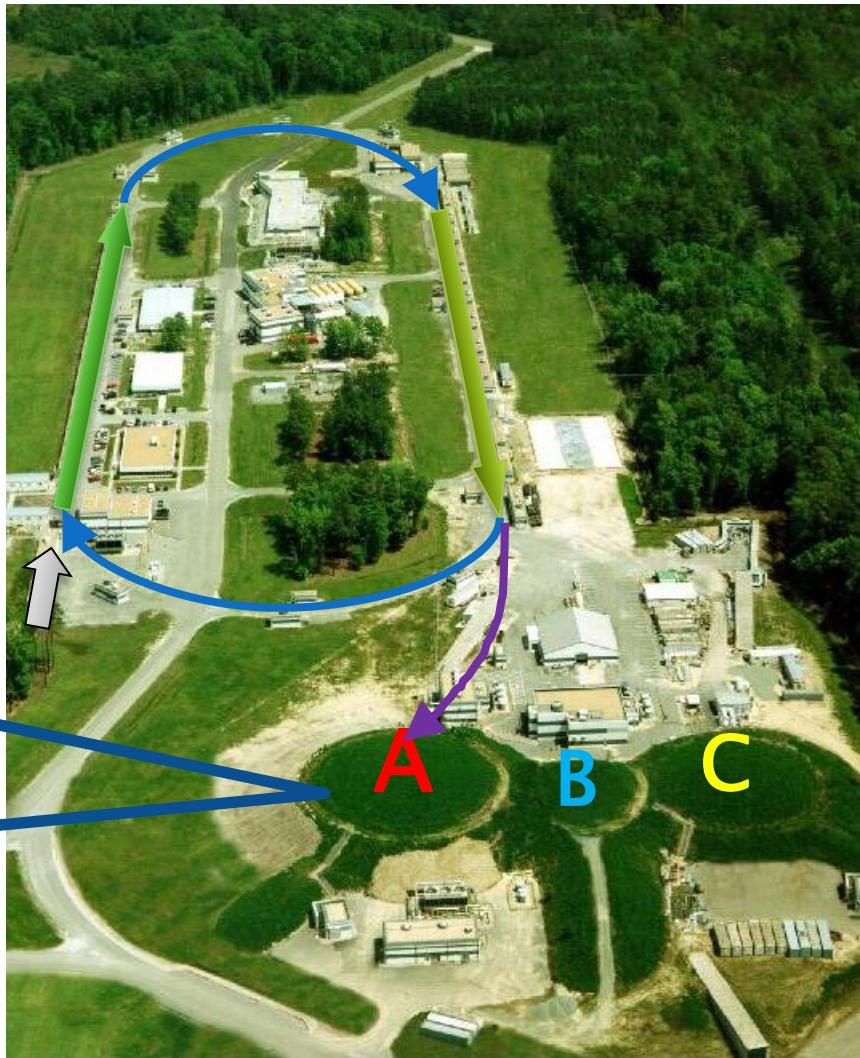
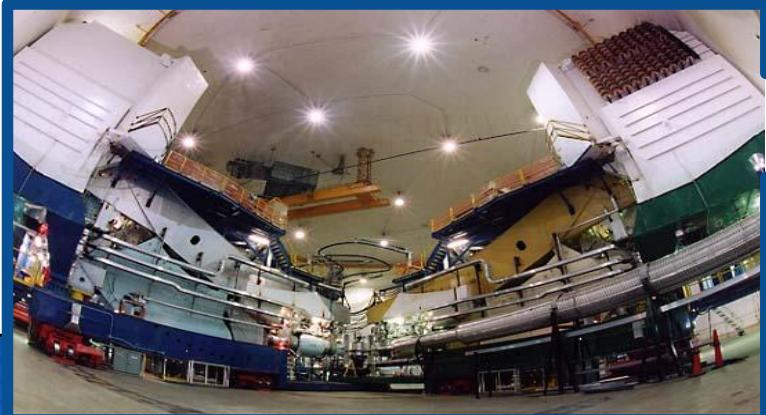
Existing Results

- ▶ No SIDIS A_{LT} measurement until 2002
- ▶ COMPASS data
 - A_{LT} on **deuteron** (\sim neutron + proton)
 - **No beam spin flip**
 - A_{LT} mixed with single target spin asymmetries
 - Extra uncertainty
 - **Low X** , small asymmetry
- ▶ New measurement needed
 - Different target for flavor decomposition
 - Higher precision
 - Valence region



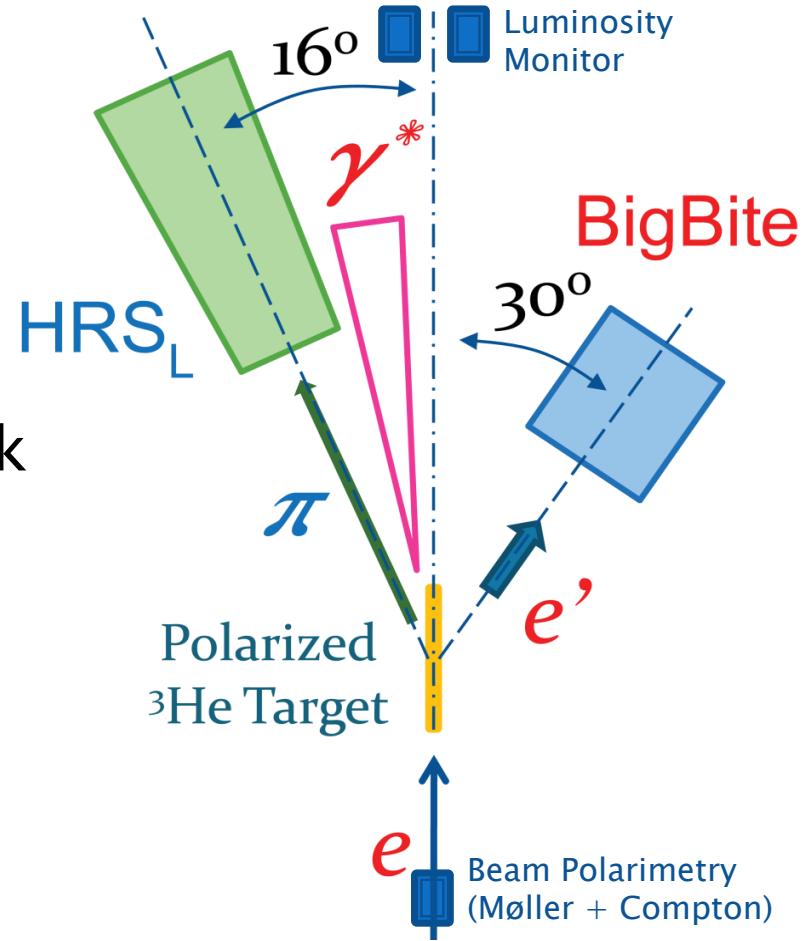
Jefferson Lab Hall A

- ▶ Newport News, Virginia
- ▶ Linear accelerator provides continuous polarized electron beam
 - $E_{\text{beam}} = 6 \text{ GeV}$
 - $P_{\text{beam}} = 85\%$
- ▶ 3 experimental halls

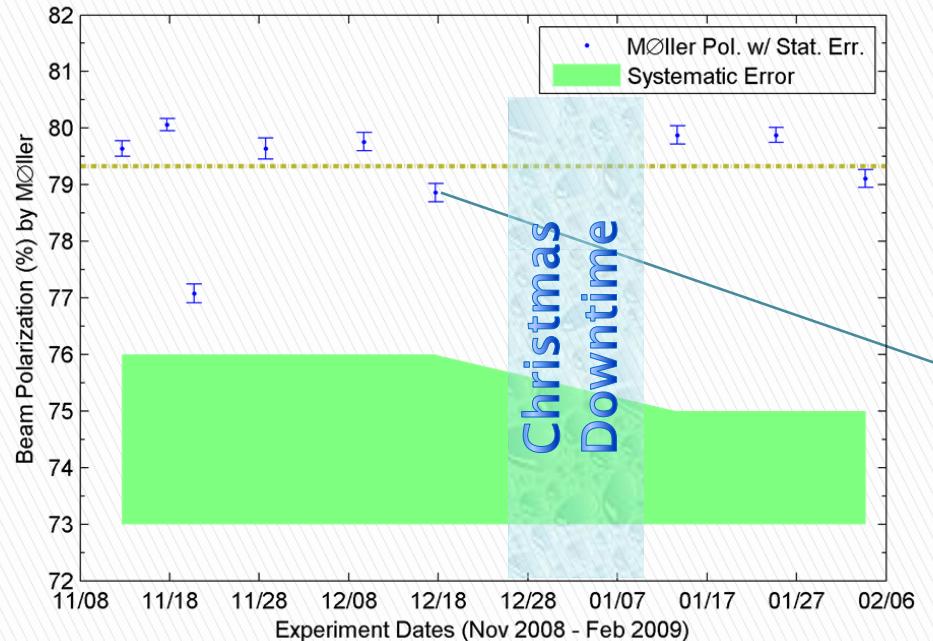
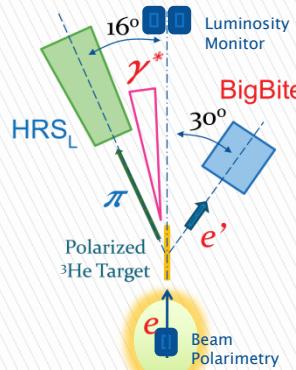


E06-010 Experiment Setup

- ▶ Polarized ^3He target
- ▶ Polarized electron beam
 - ~80% polarization
 - Fast flipping at 30Hz
 - PPM level charge asymmetry controlled by online feed back
- ▶ BigBite at 30° as electron arm
 - $P_e = 0.7 \sim 2.2 \text{ GeV}/c$
- ▶ HRS_L at 16° as hadron arm
 - $P_h = 2.35 \text{ GeV}/c$



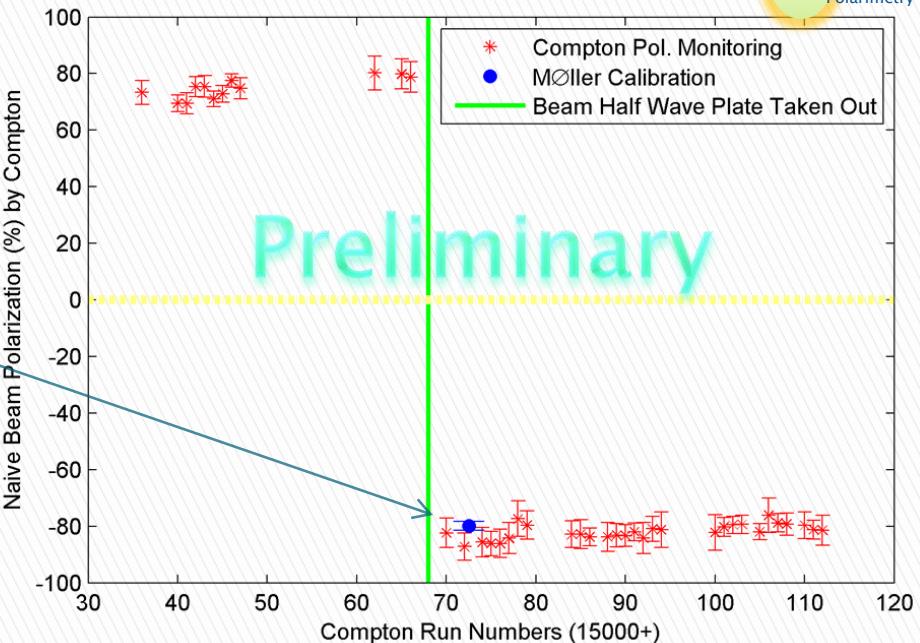
Polarized Electron Beam



- ▶ Performed per week
- ▶ Polarization $\rightarrow \sim 80\%$

Møller Polarimetry

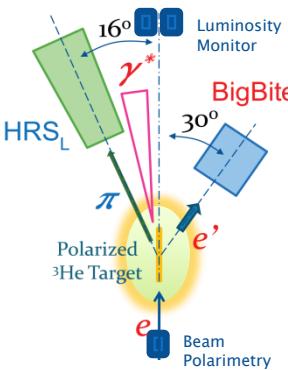
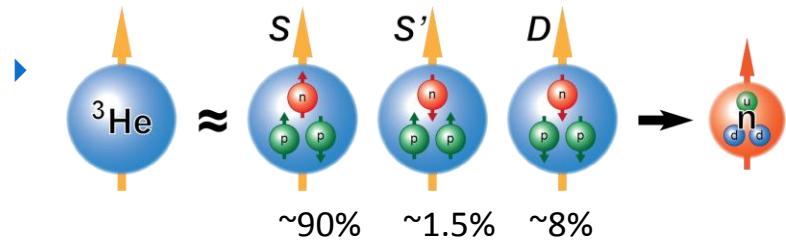
<http://www.jlab.org/~moller/E06-010.html>



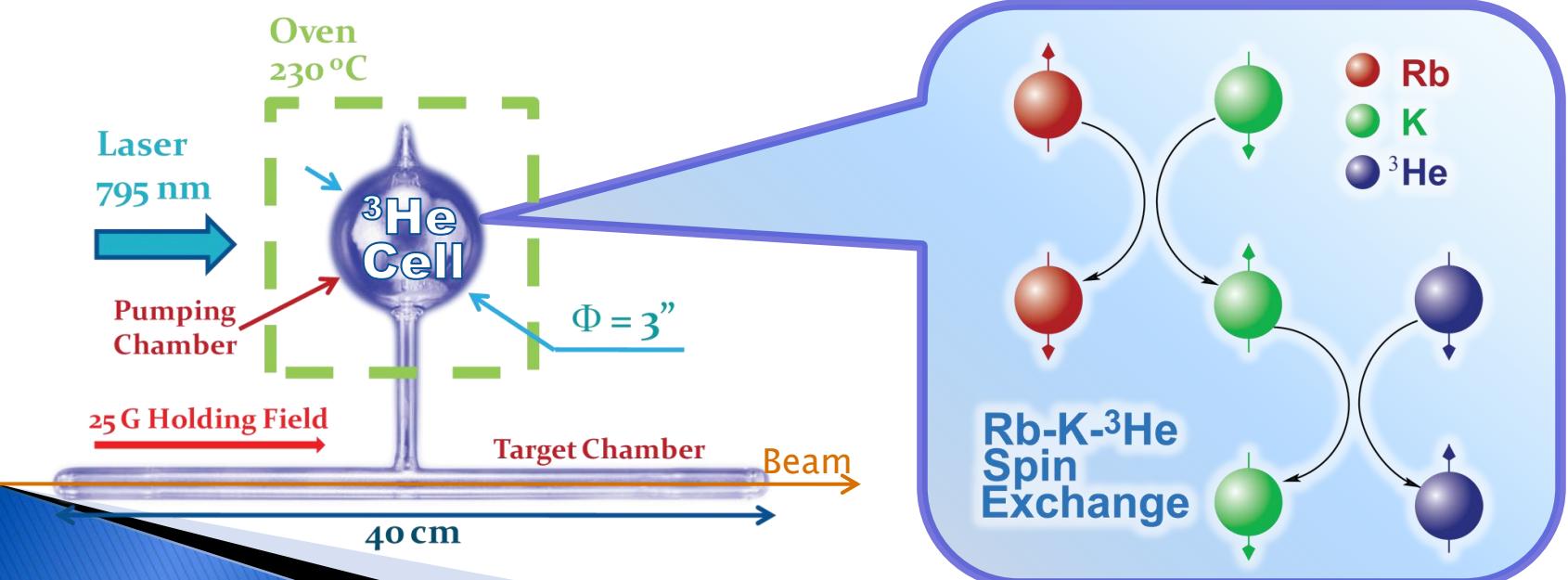
- ▶ Polarization monitoring
- ▶ Calibrated by Møller

Compton Polarimetry

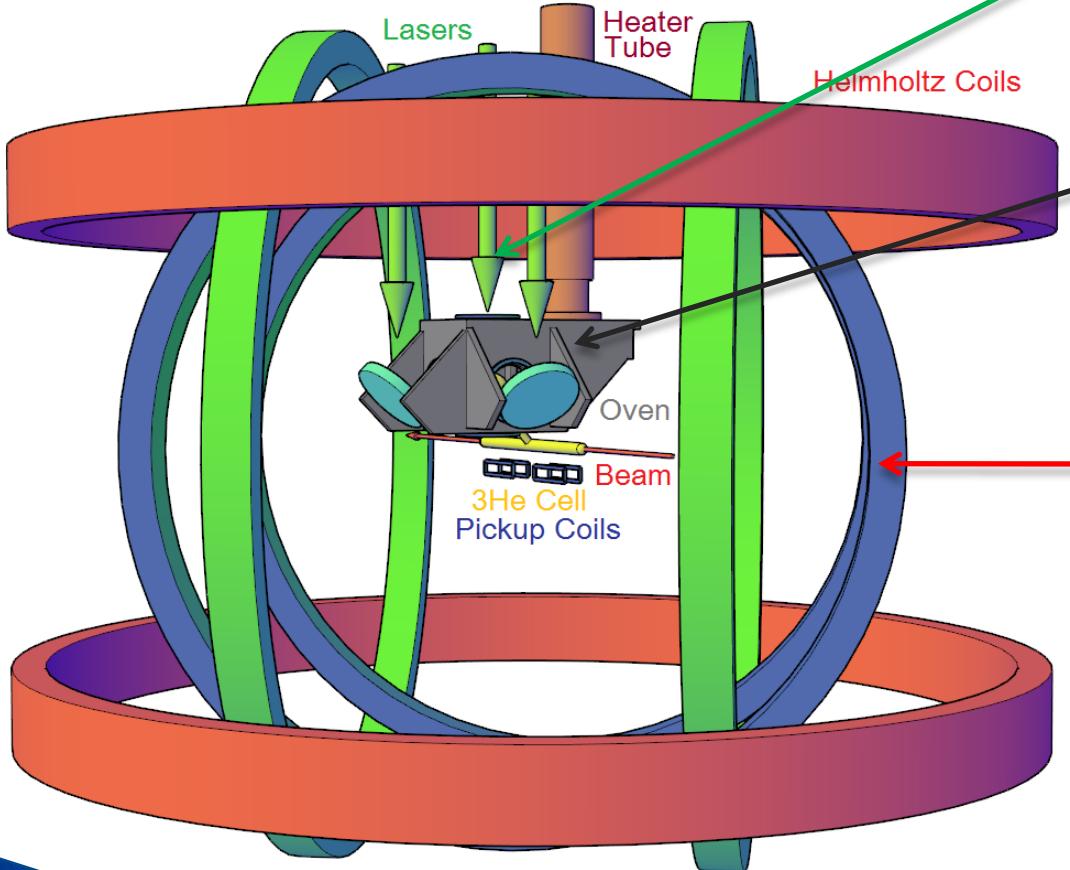
Polarized ^3He Target



- ▶ Greater figure of merit than polarized deuteron target
 - Nuclear polarization: 40~60% vs 30~50%
 - Much higher beam current
- ▶ Compact size: No cryogenic support needed



Highlights of Target Setup



New laser

- Narrow line width
- ^3He polarization $\uparrow \sim 30\%$

New optics and oven

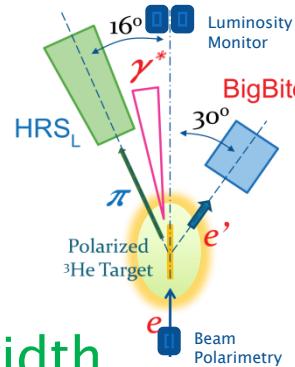
- Polarizing and polarimetry at 3 directions

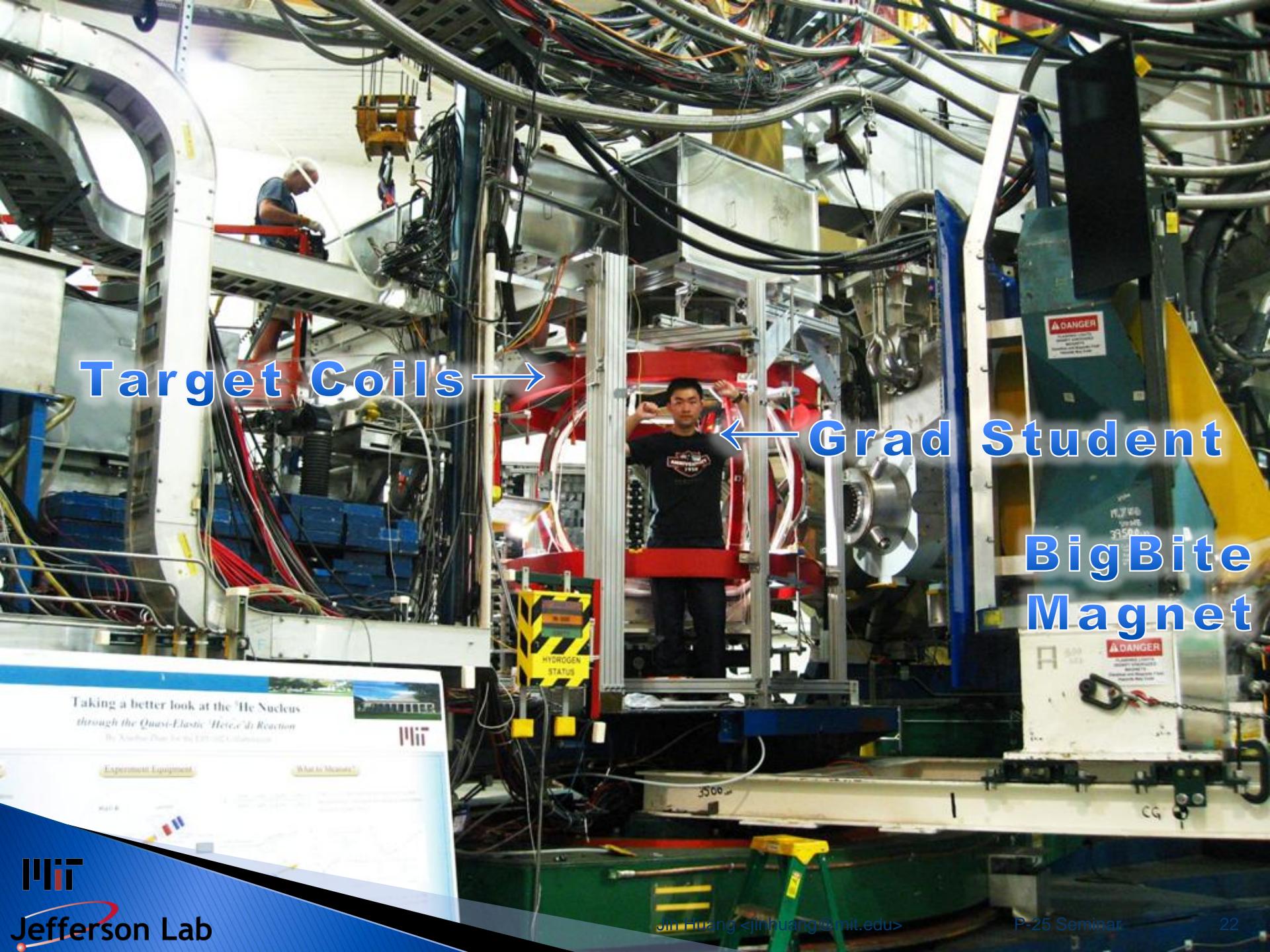
Holding magnet field

- 3D field hold spin to any direction

A smart target

- Flip ^3He spin every 20min
- $<10^3$ failure rate
- Auto analyzer, log and early warnings





Target Coils →

← Grad Student

Big Bite
Magnet

Taking a better look at the ${}^3\text{He}$ Nucleus
through the Quasi-Elastic ${}^3\text{He}(\text{e},\text{e}'\nu)$ Reaction
By Xiaoming Zhang for the E911 Collaboration

Mit

Experiment Equipment

What to Measure?

Mass

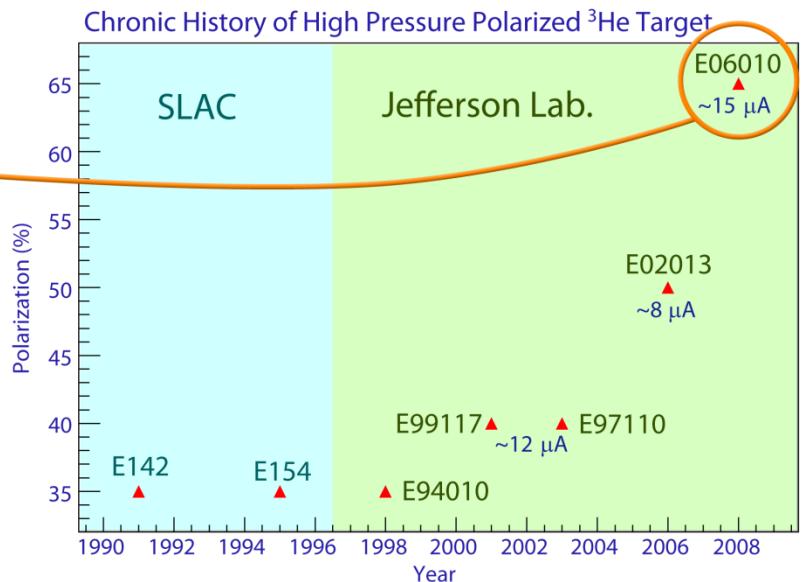
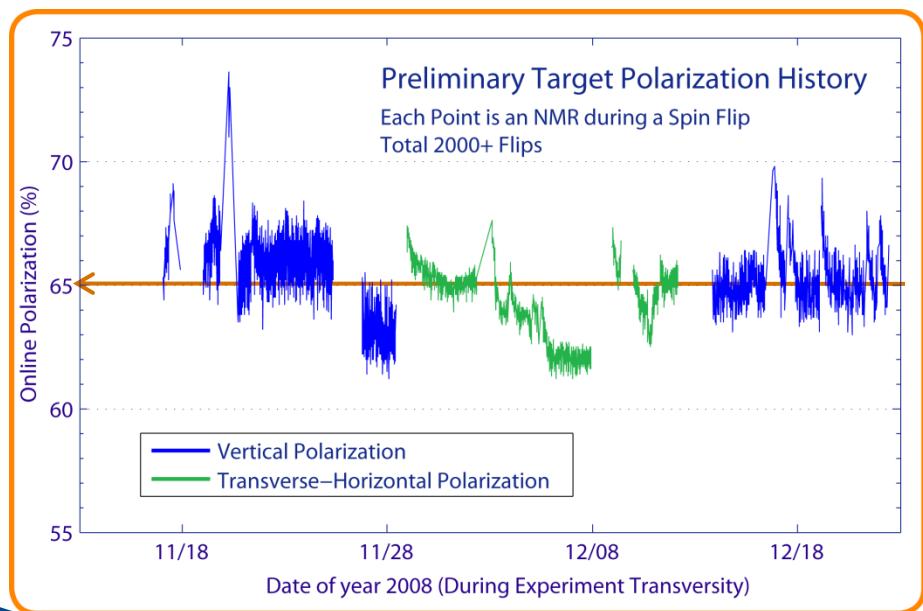
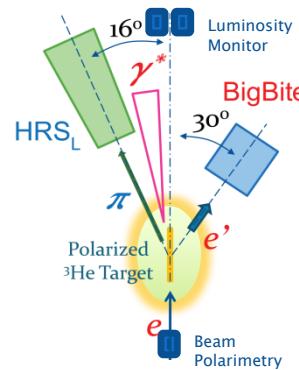
Jin Huang <jinhuang@mit.edu>

P-25 Seminar

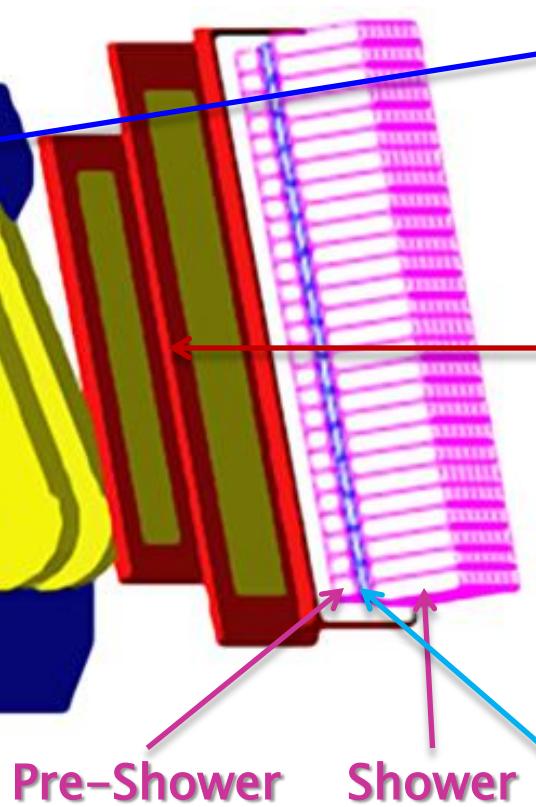
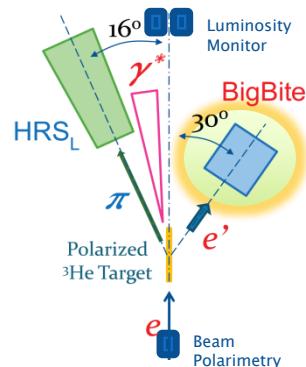
22

Performance of ${}^3\text{He}$ Target

- ▶ High luminosity: $L(n) = 10^{36} \text{ cm}^{-2} \text{ s}^{-1}$
- ▶ Record high 65% polarization (preliminary) in beam with automatic spin flip / 20min



BigBite Spectrometer

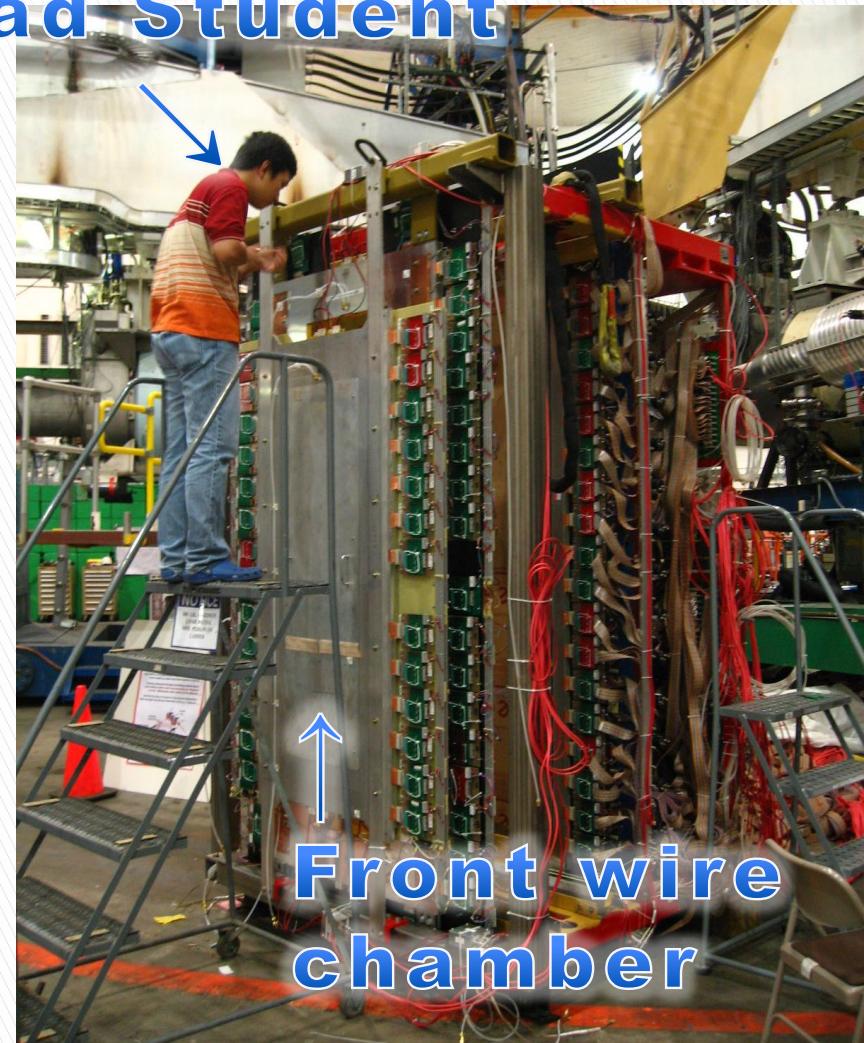


- ▶ Detects electrons
- ▶ Single dipole magnet
- ▶ A “big bite” of acceptance
 - $\Delta\Omega = 64 \text{ msr}$
 - $P: 0.7 \sim 2.2 \text{ GeV}/c$
- ▶ 3 wire chambers: 18 planes for precise tracking
- ▶ Bipolar momentum reconstruction
- ▶ Pre-shower and shower for electron PID
- ▶ Scintillator for coincidence with left HRS

Grad Student



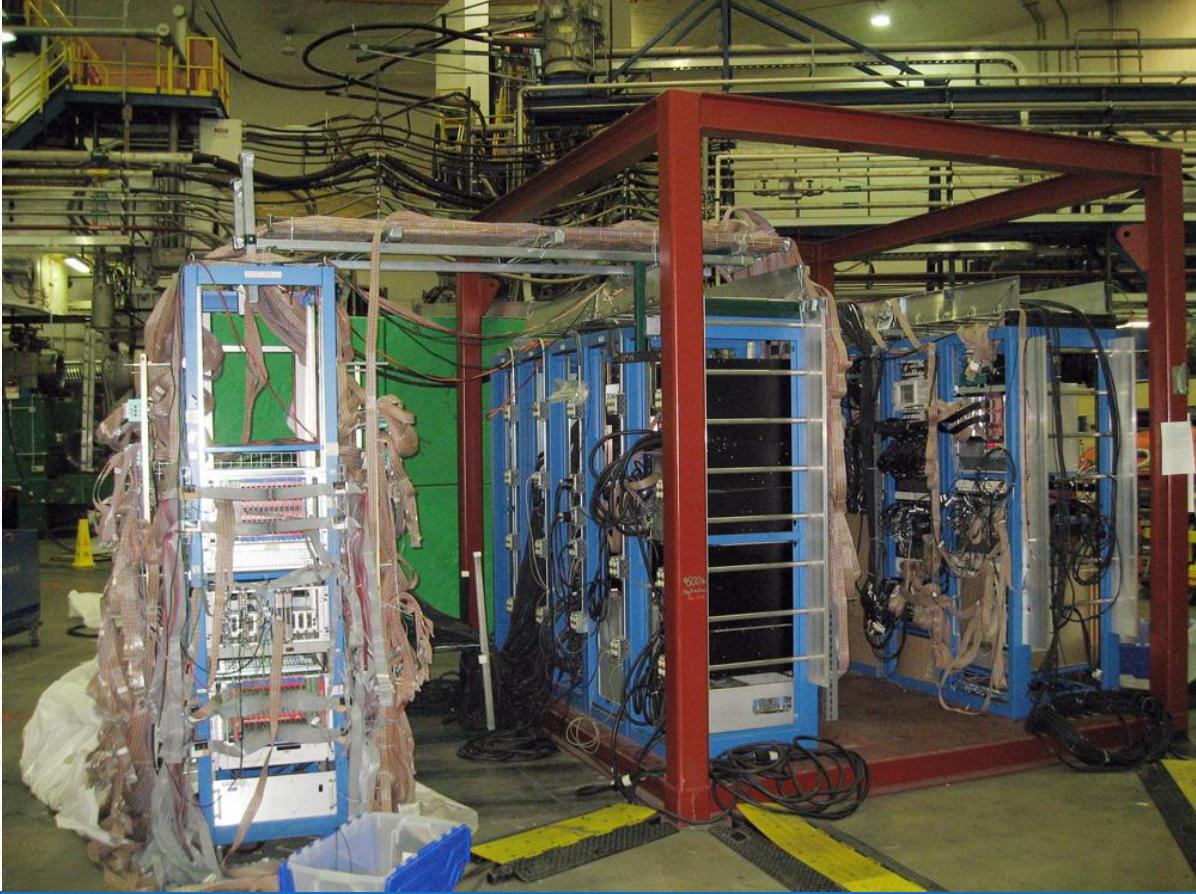
BigBite Magnet



Detector Package



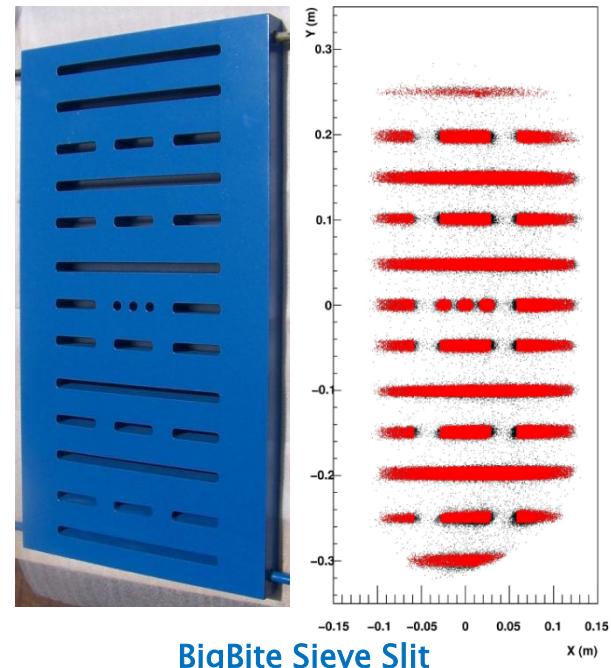
“River” of cable



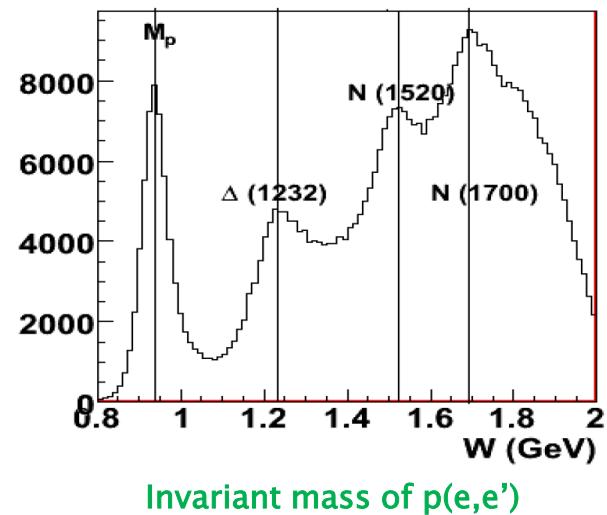
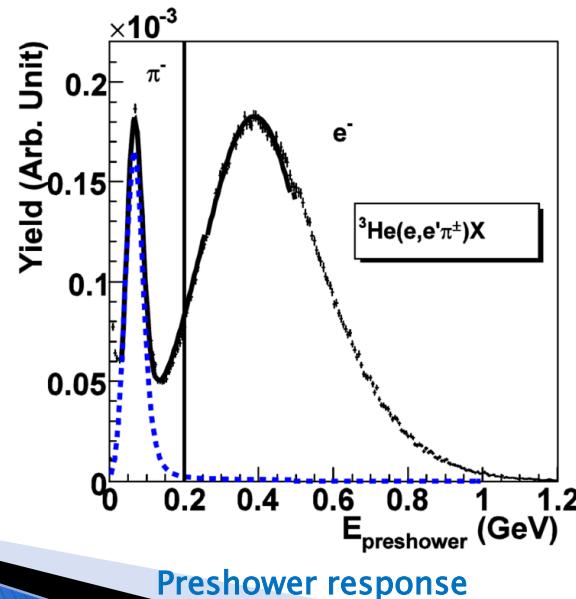
BigBite DAQ subsystem

BigBite Calibration

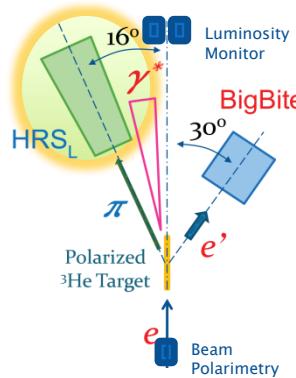
- ▶ Optics for both negative and positive charged particles
 - Chamber resolution: 180um
 - Angular resolution: < 10 mrad
 - Momentum resolution: 1%
 - Vertex resolution: 1 cm
- ▶ Clear e-pi separation with shower-preshower



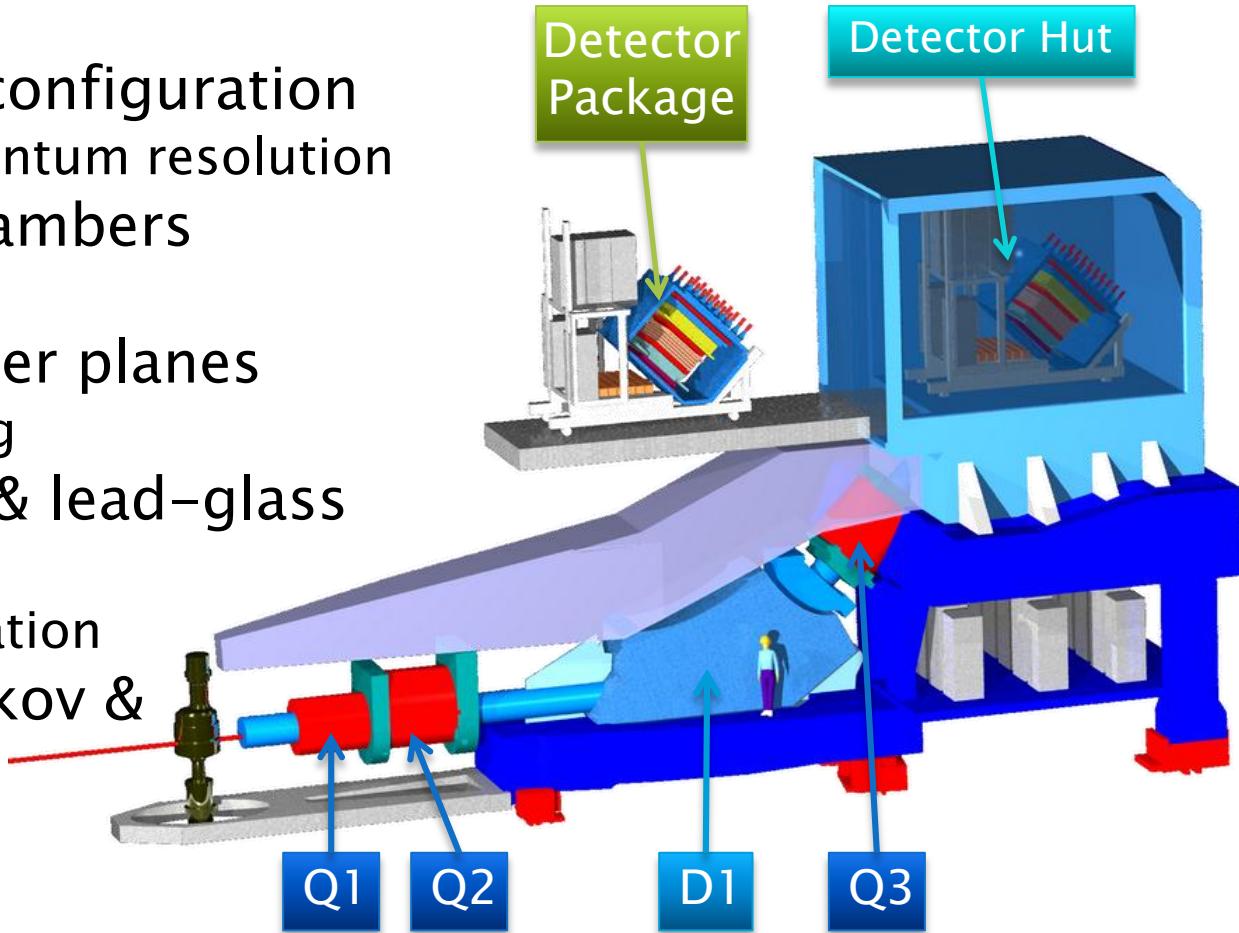
BigBite Sieve Slit



High Resolution Spectrometer (HRS)



- ▶ HRS_L to detect hadrons of $p_h = 2.35 \text{ GeV}/c$
- ▶ QQDQ magnet configuration
 - Very high momentum resolution
- ▶ Vertical drift chambers
 - Tracking
- ▶ Scintillator trigger planes
 - Trigger & Timing
- ▶ Gas Cherenkov & lead-glass blocks
 - e/hadron separation
- ▶ Aerogel Cherenkov & RICH detector
 - π/K separation





HRS

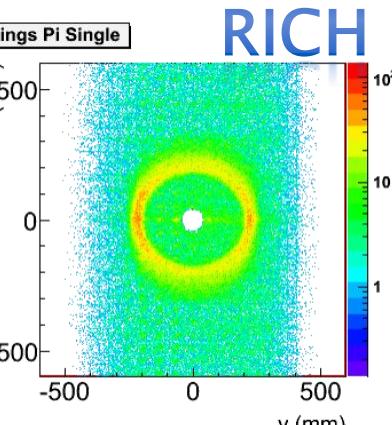
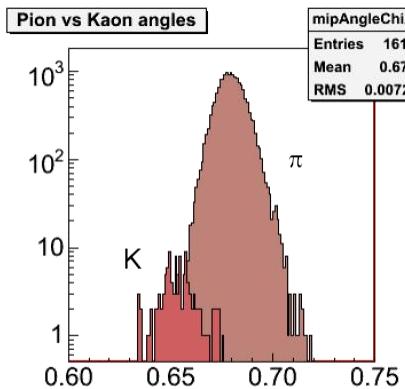


Detector Package

HRS Calibration

Detector

- Clean e/π separation with Gas Cherenkov counter and Lead-glass detector
- Kaon PID by:
 - A1: Pion rejection > 90 %
 - RICH: K/π separation $\sim 4\sigma$
- Scintillator: timing $\sigma \sim 150\text{ps}$

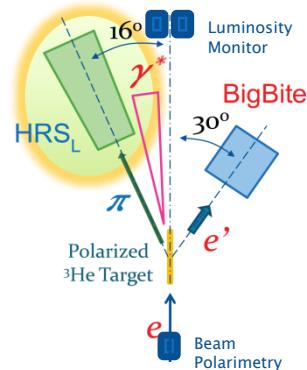
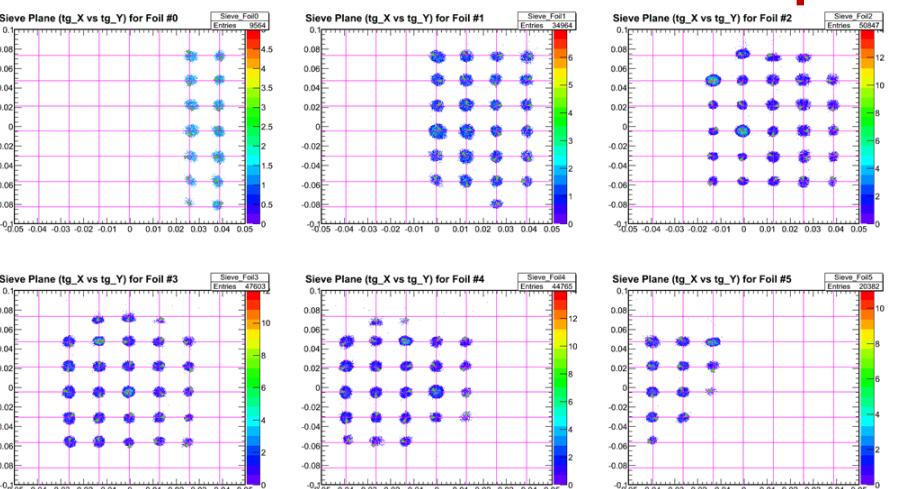


4 σ Separation

Spectrometer optics

- ▶ 3D momentum and vertex reconstructions

Optics Example:
Angular Calibration



Coincidence Analysis

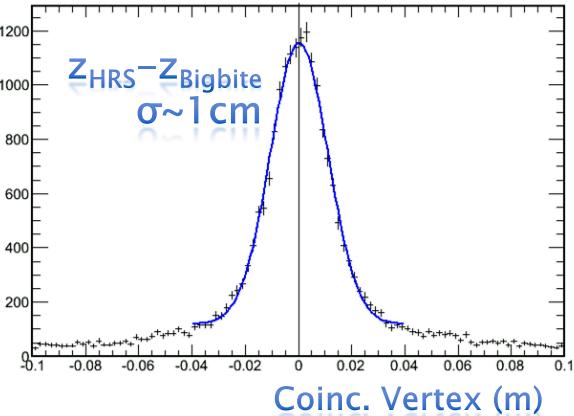
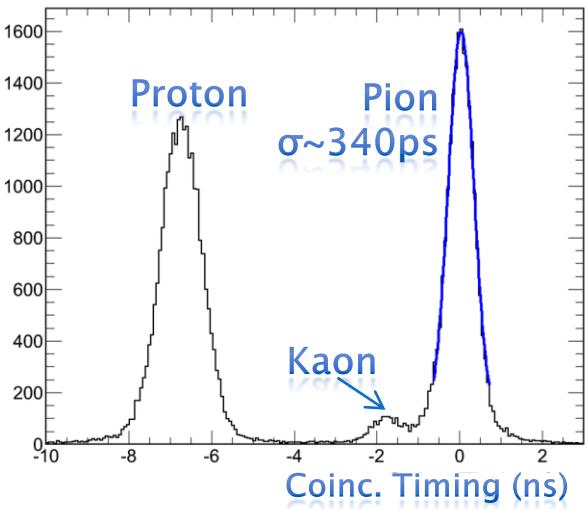
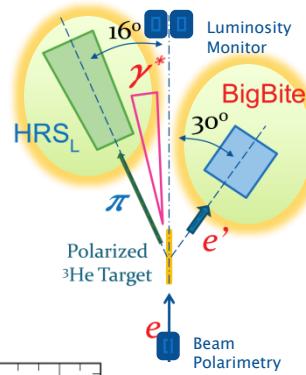
► Timing

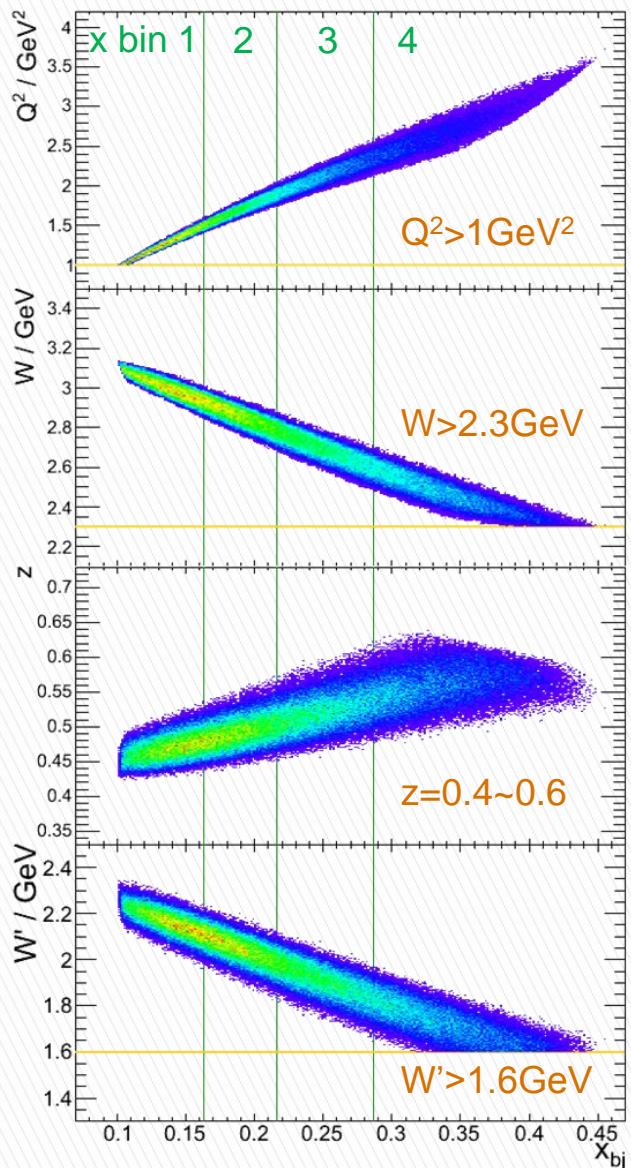
- Scintillator planes in both spectrometers
- Coincidence timing resolution $\sim 340\text{ps}$
- K/ π separation on hadron arm (+PID det.)

► Vertex

- Coincidence res. $\sim 1\text{cm}$ (Target Length $\sim 30\text{cm}$)

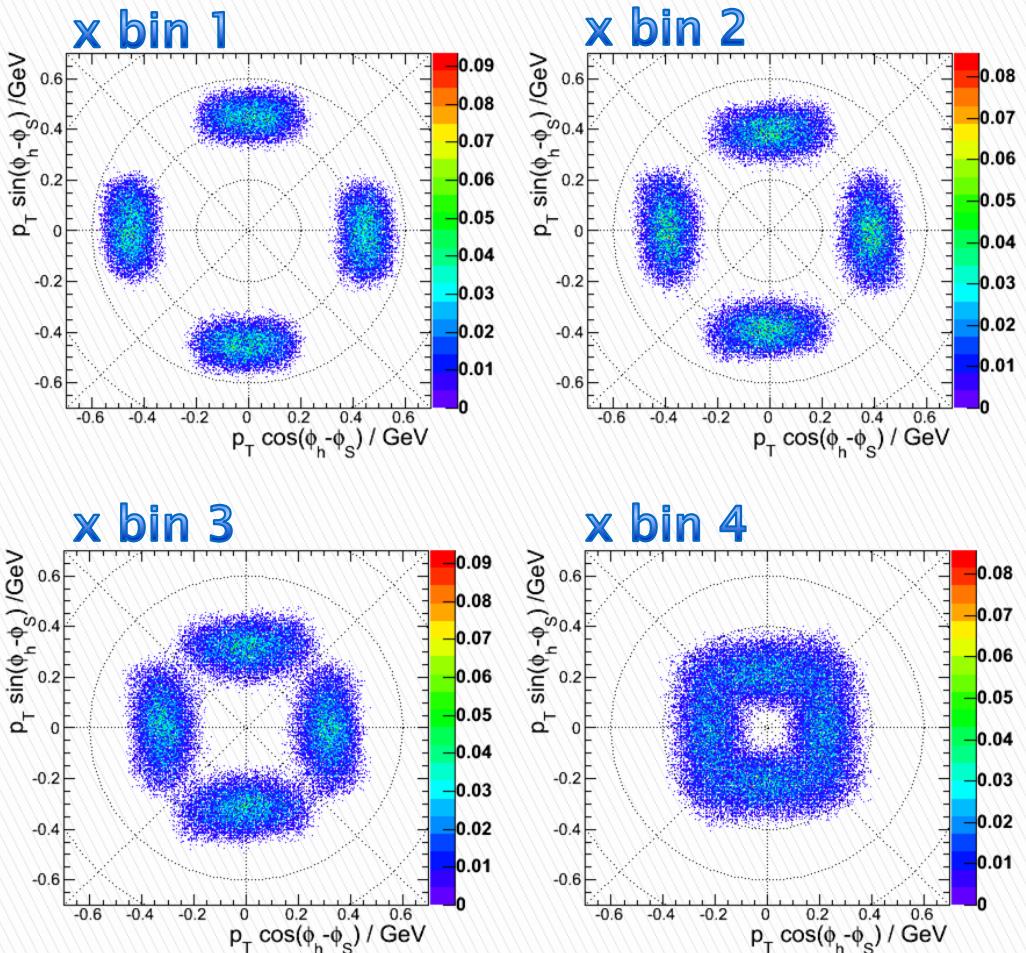
► Rand. background $<1\%$





Kinematics coverage

Data Coverage



p_T & $\phi_h - \phi_S$ coverage

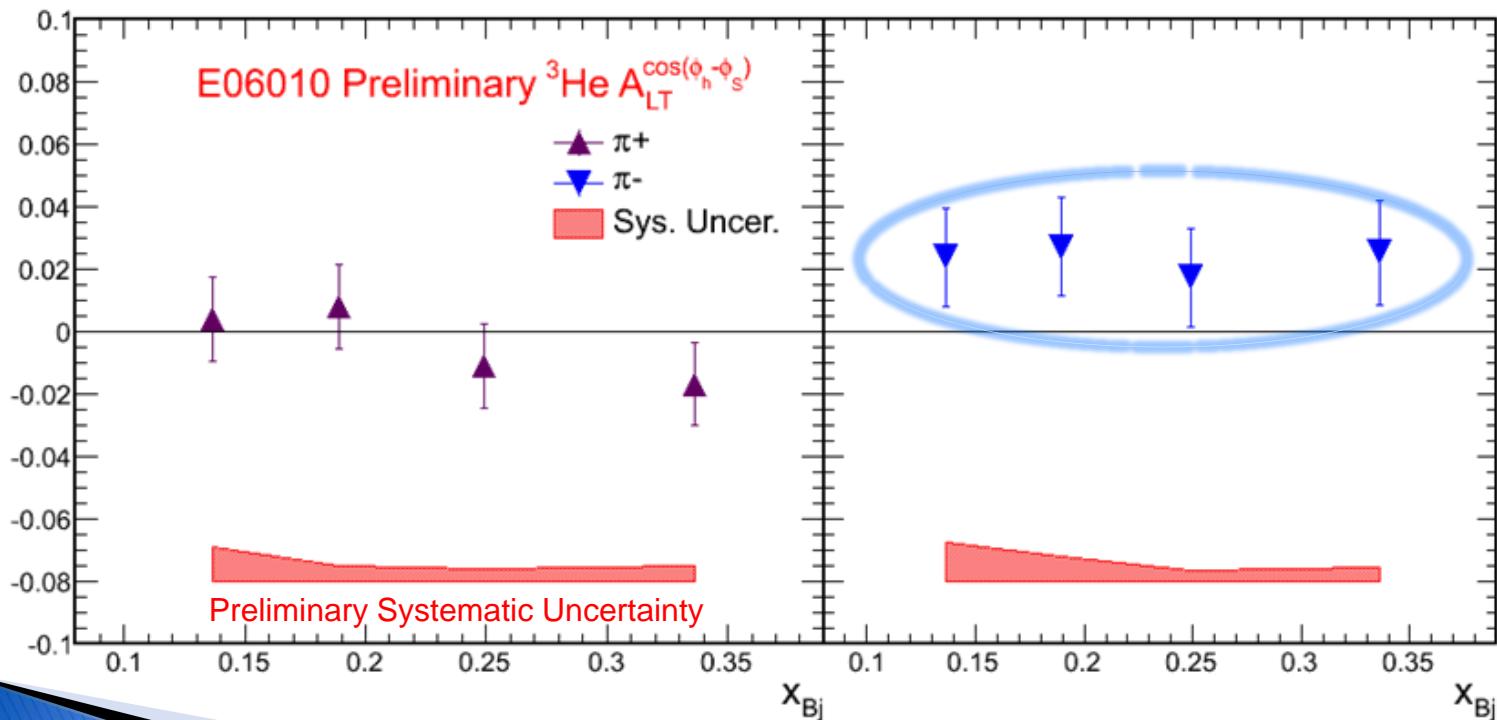
Extraction of Modulated Asymmetry

- ▶ It's not straight forward!
 - Target spin flip/angular coverage/charge, DAQ asymmetry
- ▶ Two analysis team
 - Independent after calibration
 - **Blue Team**
 - A local pair-angular bin-fit method
 - **Red Team**
 - A maximum likelihood method
 - Extract asymmetry in one step with max. efficiency
 - Tech. note: <http://www.jlab.org/~jinhuang/Transversity/MLE.pdf>
 - Result from both team agree well

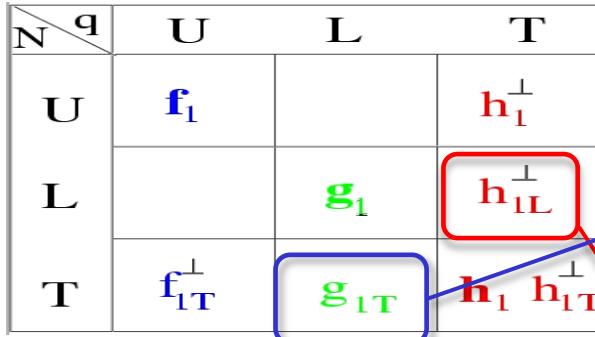


Preliminary Asymmetry Result

- ▶ Preliminary ${}^3\text{He}$ A_{LT}
 - Systematic uncertainty is still under work
 - Projected neutron A_{LT} stat. uncertainty : 6~10%

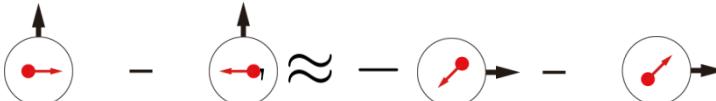


Data on Worm Gear Functions

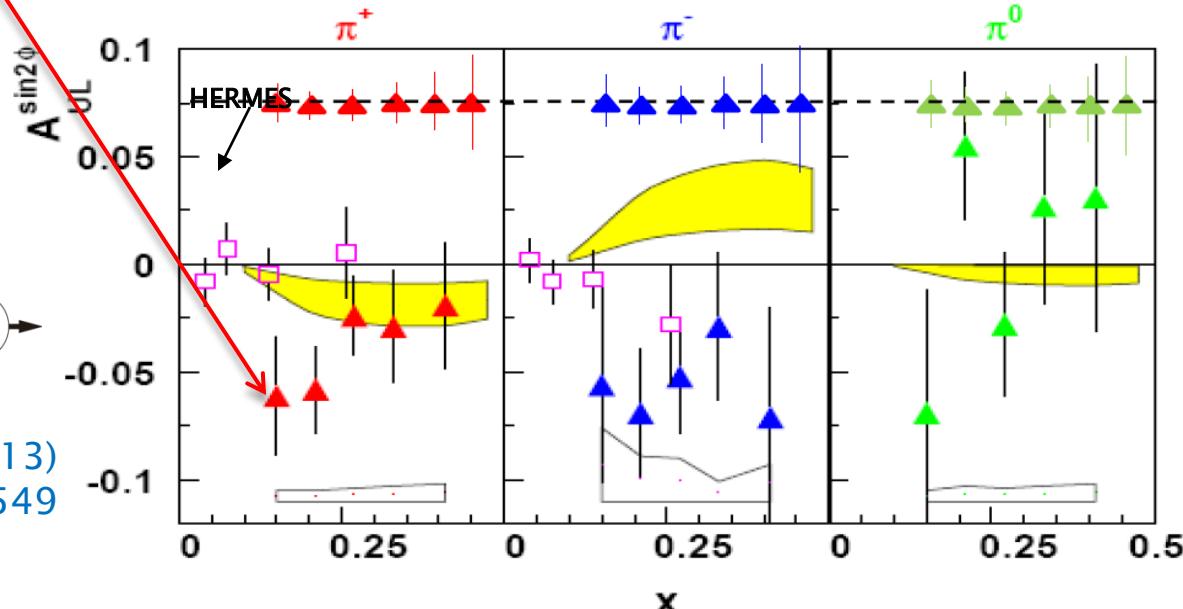
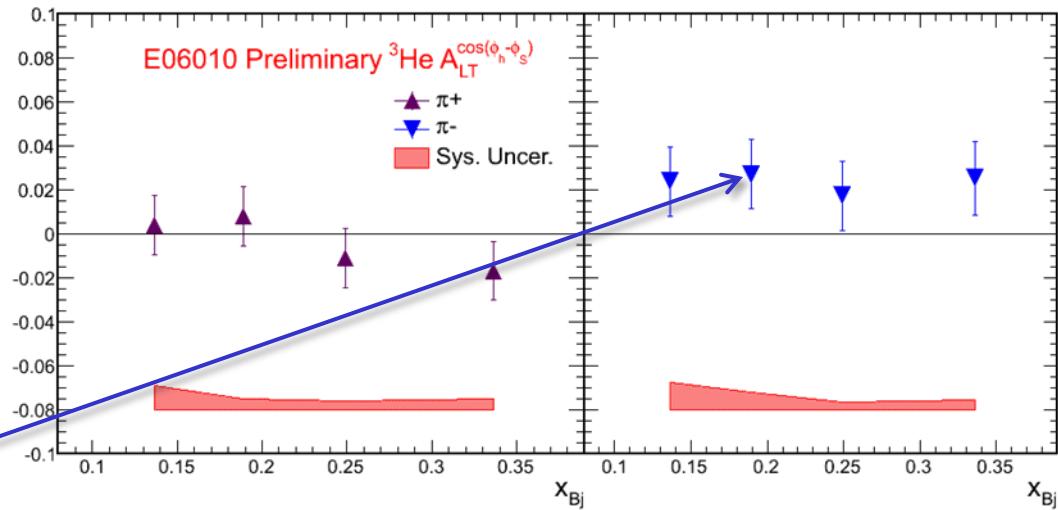


Cilindrical symmetries?

$$g_{1T}^u \approx -h_{1L}^\perp u$$

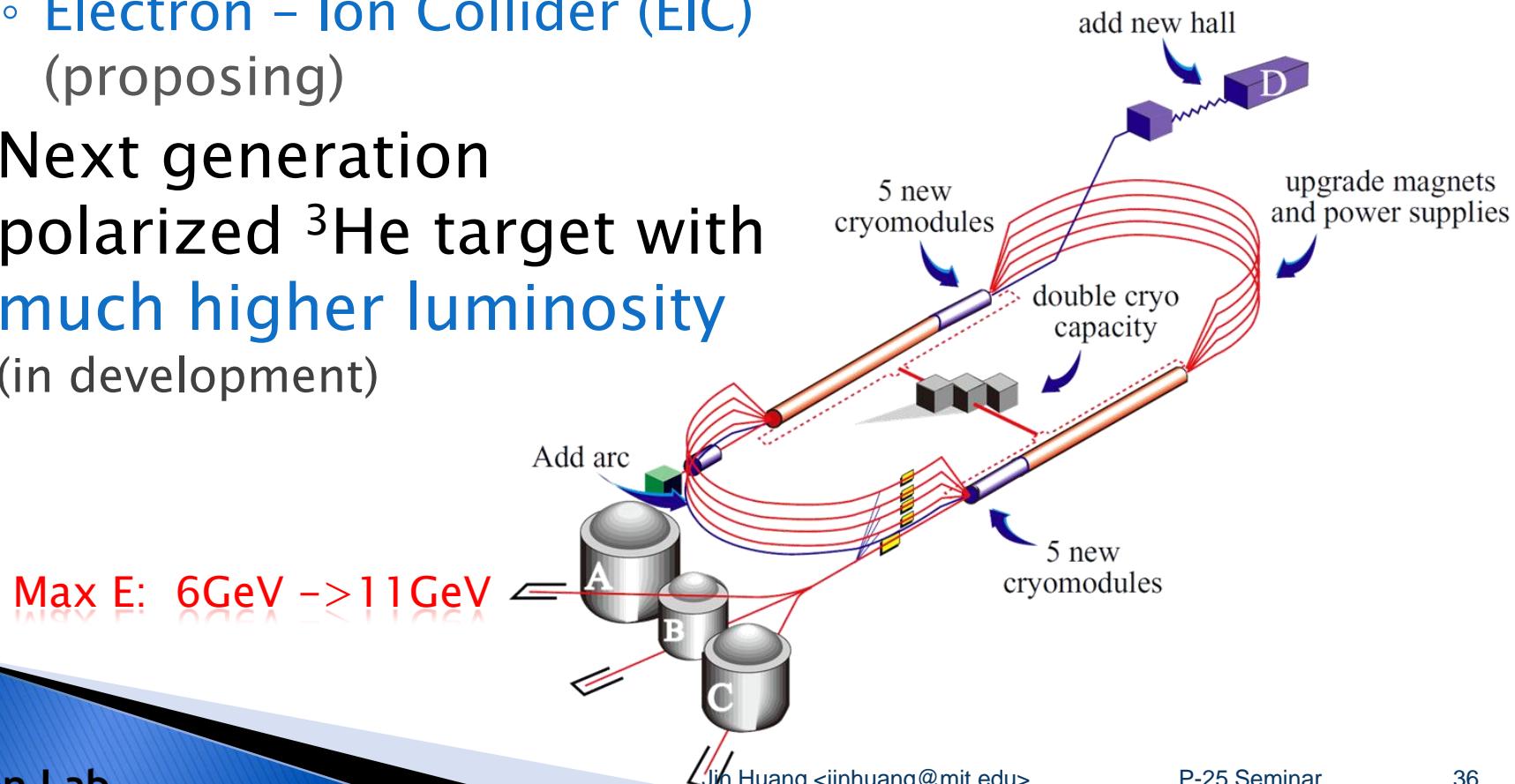


CLAS Data (E05113)
arXiv: 1003.4549



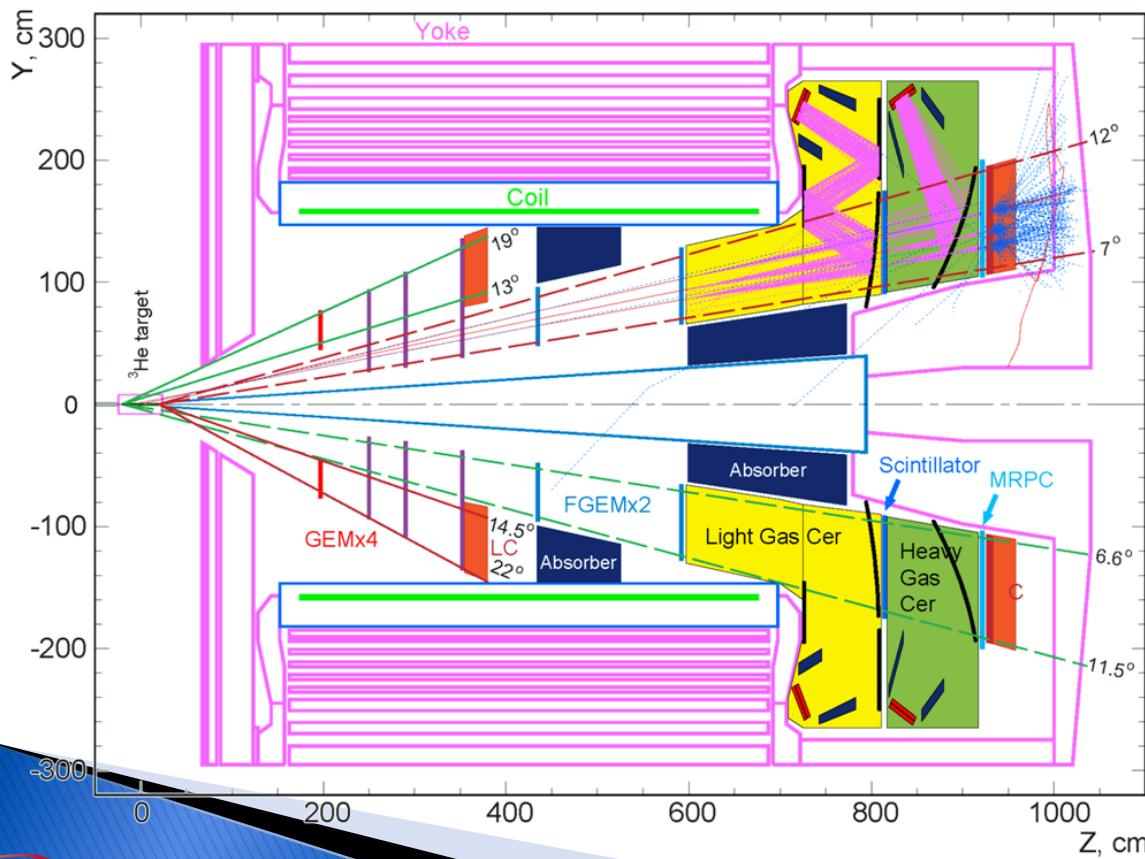
Future : Advance in beam and target

- ▶ Advance in accelerators
 - Coming 12GeV Jlab upgrade:
 - Electron – Ion Collider (EIC)
(proposing)
- ▶ Next generation
polarized ^3He target with
much higher luminosity
(in development)



Future : SIDIS with Solenoid Det.

- ▶ 12 GeV upgrade of JLab
- ▶ Approved: a **solenoid with detector package** (GEM, Shower counter, Gas Cherenkov ...).

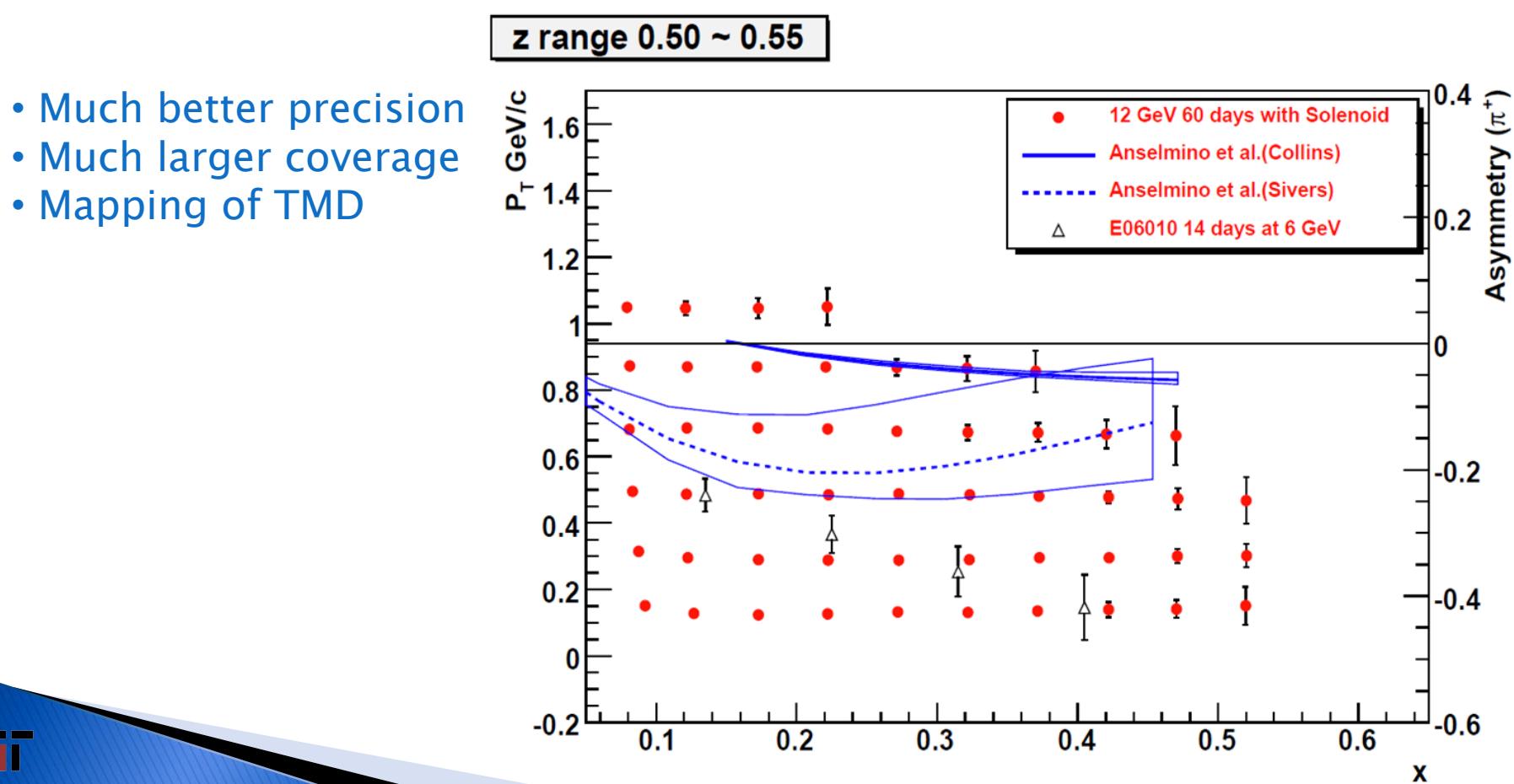


- Larger acceptance
 ϕ : 2π coverage
 θ : 7–22 degrees
 p : 1–7 GeV/c.
- Better angular dependence decomposition.

LC: Large angle calorimeter
C: Calorimeter

Much higher precision and coverage

- ▶ x, Q^2, pT, z 4D mapping
- ▶ only a sub-range of 11 GeV shown here:



Summary

- ▶ First measurement of neutron A_{LT} from polarized ${}^3\text{He}$ target
 - New view point of quark angular momentum
- ▶ Systematic uncertainties is improved by fast beam helicity flip
- ▶ Data will cover valence range
- ▶ Promising Kaon A_{LT} data
- ▶ Submitting first paper in few months
- ▶ Precision 4D mapping planed after Jefferson Lab 12GeV upgrade
- ▶ One of flagship topics for EIC (proposing)